MATTER, ENERGY AND RADIATION

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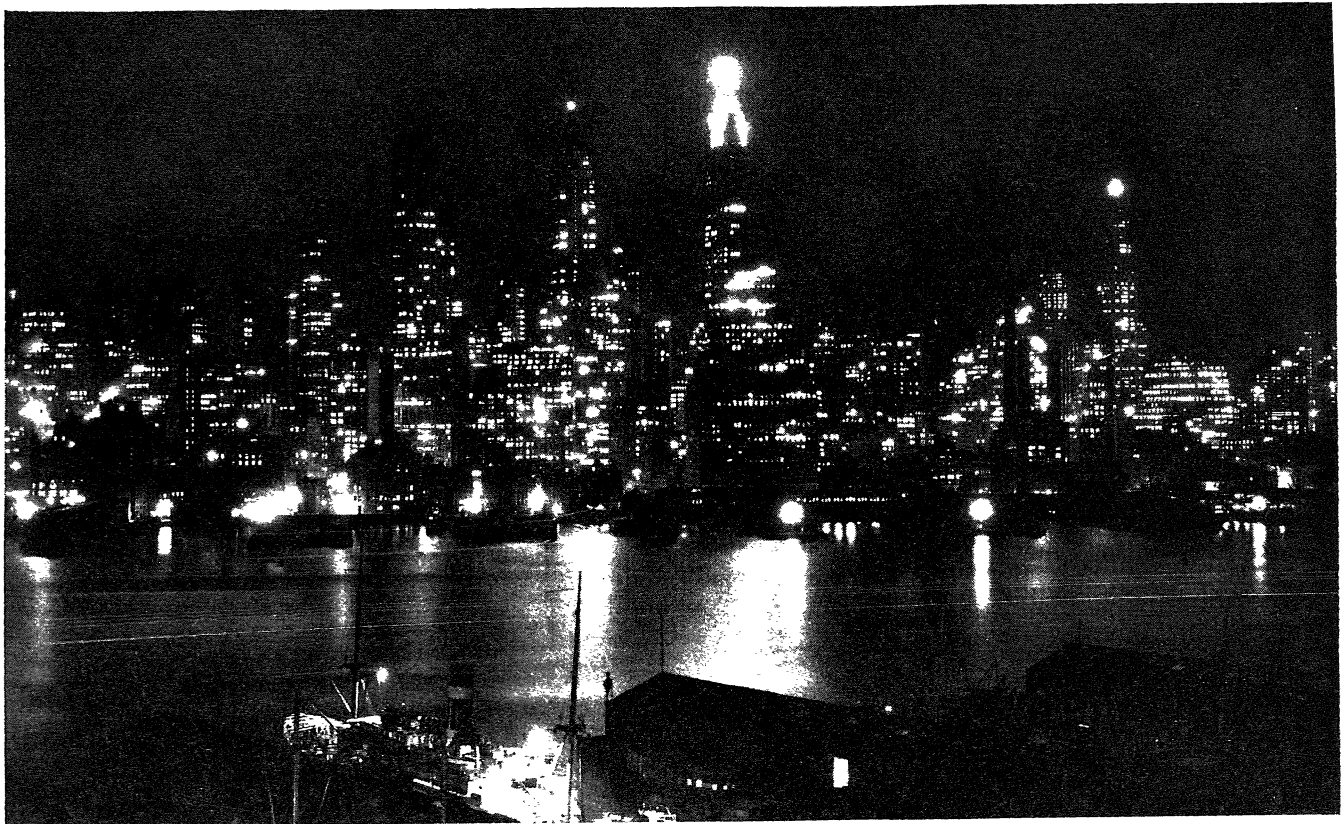

(*Consolidated Edison Company of New York.*)

Matter
Energy and Radiation

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MATTER, ENERGY AND RADIATION

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To

E. B. D. and J. T. P.

PREFACE

This text was originally prepared for students in Columbia College taking the first semester of the two-year sequence in the sciences. The designations of this sequence, arranged by semesters, are:

Science A1—Matter, Energy, and Radiation
Science A2—Chemical Changes in Matter
Science B1—The Earth, Its Origin and Physical History
Science B2—Transformations of Matter and Energy in Living Organisms

This two-year science course was developed as a cooperative program involving the various science departments, because the faculty has increasingly felt that there was a serious need for a broader basis for the science training and that the traditional single year of a specific science and of mathematics did not provide sufficient opportunity for an acquaintance with and understanding of the main facts and principles, the methods, the thought, and the dominant trends of modern science. After considerable testing and experimentation over a period of six years, the committee in charge of the course has concluded that the success of the program warrants publication of texts in the hope that they may prove useful in other colleges and universities where the problems of liberal education are leading to the development of integrated science programs.

The whole course and the series of four books being prepared for it are designed for those students who do not intend to enter the sciences professionally, but who do desire a general acquaintance with the chief fields of scientific investigation, a discussion of the major problems, concepts, and theories in these fields, and an introduction to experimental techniques. Its aim is to present as systematically as possible those themes of modern science that are of fundamental significance and general interest. Various phases of the same field are frequently treated in different parts of this course. The student has been encouraged to go as far as he wishes in any particular phase of science in which he might show

especial interest. The course is conceived as a unified program of study which will satisfy the science requirements for the degree of Bachelor of Arts.

This book, primarily in physics and in certain aspects of astronomy, is intended to guide the student's thinking and to serve as the principal reference text. It focuses attention on three major concepts, **matter, energy,** and **radiation,** emphasizing important subtopics and introducing the more vital questions in the various fields without going into the minor details more than is necessary to give a reasonably well-rounded whole. In order to take full advantage of the opportunities offered, the student is encouraged to read widely from the list of suggested references at the end of each chapter. A series of questions is also included to stimulate discussion and to crystallize the student's thought.

This and the other texts of the series are designed to form an integrated whole. Many departures have been made from conventional courses, which in a sense have generally evolved in the direction of professional preparation. At the same time, this course is meant to be much more than a mere survey course in science. The texts are emphatically not intended to be merely **about** science—they are intended to be texts **in** science. The Science Committee feels strongly that science is so important in the present-day world that a college student should have an opportunity for a real acquaintance with it and that sufficient time should be allotted in the college curriculum to encourage more than a fleeting survey.

The Committee believes that for the student really to appreciate and understand the methods of science he should if possible have some opportunity to work with his own hands in the laboratory. For that reason a weekly two-hour laboratory period has been included in the course. However, the texts are designed to be as complete as possible so that they may be of service even in those institutions where such a laboratory program is not feasible. The laboratory work differs considerably from the conventional type and is carefully planned to capture the student's interest as well as to illustrate fundamental principles. A general outline of the laboratory program is given as an appendix of this text, and a more complete manual is in preparation.

Where possible, it has been found valuable to supplement the laboratory work by organized field trips and individual visits.

Places of particular interest have been the Hayden Planetarium, the Rutherfurd Observatory, the New York Museum of Science and Industry, various research laboratories, and institutions and industries that show the application of science in the social order. Trips that illustrate the importance of science in the transfer and control of energy, the development of communications, and the maintenance of transportation systems have been found especially valuable.

The members of the committee in charge of the course, Professors C. O. Beckmann, A. K. Lobeck, H. B. Steinbach, H. W. Farwell, C. D. Carpenter, and J. H. McGregor, have given valuable suggestions and assistance, and a special word of appreciation should be added to acknowledge the encouragement and support of the chairman of that committee, Dean Herbert E. Hawkes. The authors are greatly indebted to their colleagues in the Department of Physics, and especially to Professor H. W. Farwell, whose efforts and ideas have contributed so much to the development of the course and to this text. They also wish to thank Mr. Harold Goldberg for his able assistance with the drawings.

J. R. DUNNING,
H. C. PAXTON.

PUPIN PHYSICS LABORATORIES
COLUMBIA UNIVERSITY,
November, 1941.

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Section I

SCIENCE

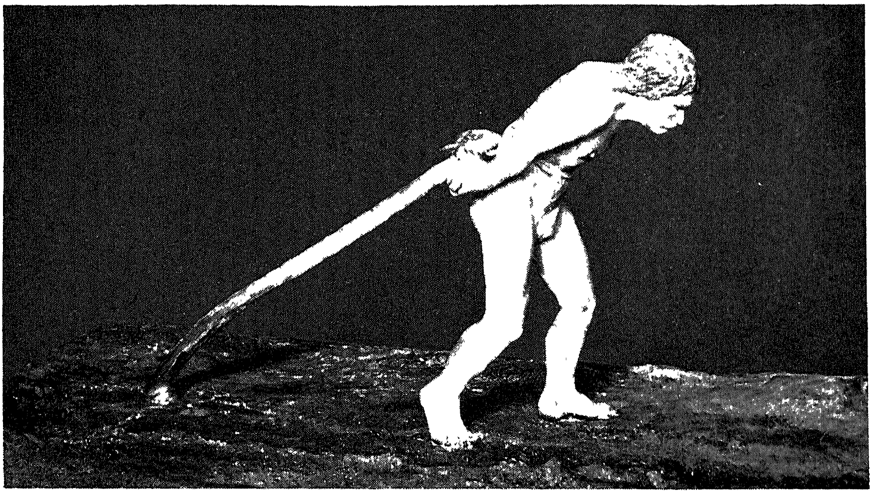
CHAPTER I

SCIENCE AND CIVILIZATION

SCIENCE AND THE MODERN WORLD

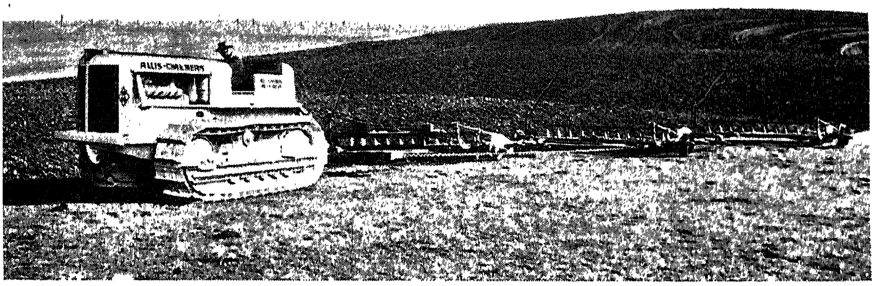
Today we see a world in which the social, industrial, and political order has been influenced profoundly by science. The rapid development of science within the past few hundred years has already increased man's understanding and consequent mastery of nature so greatly as to affect the whole material side of life. This change has been swift if one considers man's long history.

Civilization Is Young. Man has probably existed on earth for some 200,000 to 500,000 years. In order to visualize human accomplishment more strikingly, let us imagine this whole period compressed into a single century, so that man first began his history about 100 years ago. On this scale, about 98 years elapsed before he had progressed from a state of virtually naked, animal savagery and was ready to give up his life as a nomadic hunter to settle down, till the soil, domesticate animals, and weave fibers into crude garments. About the end of the ninety-eighth year, writing was invented, making possible wide communication and ensuring the perpetuation of the records of civilization. Early science expanded, while art, literature, and music flourished in Greece about six months ago. Four months ago, the Christian era began. The printing press is just a month old. Three weeks ago the era of modern experimental science had its beginning. The steam engine has been with us only two weeks. Just five days ago transportation facilities began to expand when steam power was first harnessed to move railroad trains and propel steamships. A few days ago man hardly dreamed of the applications of electricity. Communication possibilities grew rapidly when the telegraph, the telephone, and finally radio arrived, so that all peoples could be brought into close contact. Only a couple of days ago man learned to fly, and in effect the world has continued to grow smaller and smaller ever since.



(*New York Museum of Science and Industry.*)

Fig. 1a. Primitive man tills the soil.

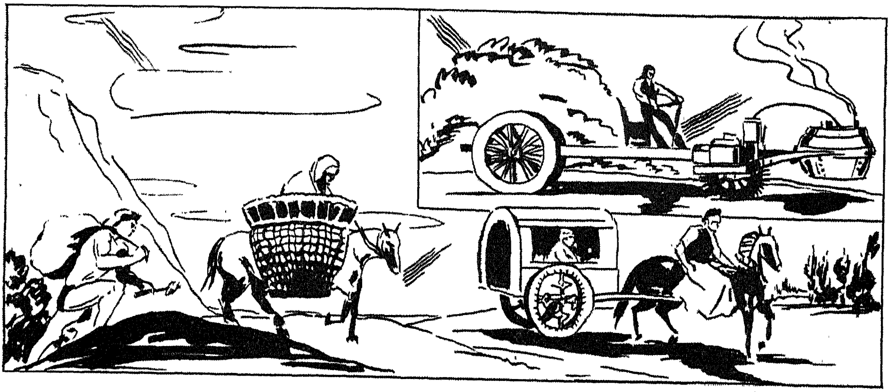


(*Allis-Chalmers.*)

Fig. 1b. Modern plowing.

Yesterday man's inventive genius turned to large-scale warfare and some 15,000,000 were killed in the First World War. Far from settling political, social, and economic problems, it actually intensified them, and proved to be but the preliminary to a second world conflagration on a still larger scale.

Civilized man has made many bad mistakes, but he is indeed only in his infancy. Compared with man's entire history, our modern world is very new, and the possibilities for material and social improvement are hardly conceived, let alone achieved. Yet, in spite of many shortcomings, man has made tremendous advances for a creature who was no better than a savage a few centuries ago.



(*General Motors.*)

Fig. 2. Stages in the development of transportation.

The growth of science and its thorough application to the world around us really has just begun. One should not be surprised, then, to find that the scientific method has been virtually unused in most areas of human thought and activity. Even now a great body of people have no real understanding of objective scientific thought. Science has contributed far more to man's material life than to the solution of his social problems.

The Increasing Role of Science in Civilization. As civilization progressed, science played an increasingly prominent part. It is quite logical that we should make much more rapid progress in understanding and controlling the inorganic physical universe than in understanding and controlling the more complicated biological and social phenomena. As we might expect, the methods of science have been evolved and applied in the fundamental natural sciences rather than in the social fields.

The developments arising from scientific thought and experiment represent a large part of the material growth of society. For example, man's increasing knowledge of the properties of matter and of the latent possibilities of the use of energy has led to ever-greater use of our natural resources.

From the dawn of history until not much more than a hundred years ago, man's fundamental needs for food, clothing, and shelter could be met only by the work men could do with their own hands and with the aid of a few animals. The Industrial Age became possible when contributions to the sciences of mechanics and heat enabled men to make better use of water power and showed them how to use coal for steam power. Through the additional utilization

of gas and petroleum and the rapid expansion in the control of electric energy, we are now at the point where, in the United States, more than one horsepower is working continuously for each inhabitant. Man's increasing control and use of energy are not only making it possible to provide material necessities and luxuries, but are also freeing him more and more from the need of spending his entire time in the struggle to provide the minimum requirements for existence. The opportunities to raise the cultural and spiritual level of society that this added leisure promises for the future are almost unlimited. Of course, these opportunities must be studied and used, not abused, if their full value is to be realized. Great social problems are waiting to be solved, and it is difficult to escape the conclusion that methods of science must play a considerable part in the solution.

Science for Those Who Are Not Scientists. Few of the students in our colleges and universities expect to become professional scientists, such as chemists, physicists, or biologists. Most of them will become lawyers, journalists, businessmen, or politicians. This is the group which, to a large extent, will supply the leaders in the various fields of human activity for the near future.

For many reasons it is essential that these young people have an opportunity to become acquainted with the methods, the thought, and the achievements of science. All of them will find, no matter what their future occupation, that their environment and even their individual work will be affected more and more by science. That students should pass through college without experience in fundamental science, and take active part in a world where science has become one of the most important factors, would be little short of tragic.

Furthermore, the achievement of anything like the level of civilization that our new mastery over nature makes possible depends in great part on those who are the leaders in fields other than the natural sciences. Research in pure science reveals the possibilities in nature, but the responsibility for placing this knowledge in wide operation rests on the leadership in the social sciences, in government, in industry and finance. The man in these fields needs some understanding of what pure and applied science is doing, and some experience with the objective methods of science

which have worked so successfully with nature and which should find greatly widening application in other fields.

From a broader point of view, it is difficult to concede that a person really can be educated unless he has some understanding of the physical world. From a cultural standpoint, appreciation of nature surely is as important as art and literature. As one looks back on history, it is evident that men of science have made a far more profound impression on the life and thought of our times than have the petty generals, the kings, and the dictators who seemed so important at the moment. The revolution in mode of thought, procedure, and outlook in contemporary life brought about by science is so challenging that no education that neglects this phase of culture can be considered complete.

Scientific Fields. The realization that college students should have an honest opportunity to become acquainted with science has caused many institutions to broaden the bases of their science programs. Heretofore it has been possible for many students to go through our colleges with little contact with the fundamental sciences, or with an acquaintance in only one limited field. The traditional courses in subjects such as physics and chemistry have so evolved that their form and content are directed more toward those who expect to specialize in these or related fields.

In the beginning, there were of course no clear divisions in science. Natural philosophy embraced all the sciences and all fields of thought. Aristotle was generally conversant with all the types of known natural phenomena. As the sciences developed and the various lines of thought expanded, it became less and less possible for one man to know all the branches. Specialization became necessary. Even so, many of the earlier men of science ranged their interest across a number of fields. Should one, for example, call Galileo a physicist or an astronomer? Was Newton a mathematician or physicist? Pasteur a chemist or biologist? Helmholtz physician or physicist? Geikie a geologist or anthropologist?

The distinctions which gradually arose were somewhat arbitrary and mostly matters of convenience. Physics came to be concerned chiefly with problems connected with matter and energy, chemistry with phenomena associated with the transformations involving all the multitude of compounds in which matter may

be found or made, biology with living matter, etc. This specialization has naturally continued until, to take chemistry as an example, we have a whole gamut of subdivisions: inorganic and organic chemistry, analytical chemistry, electrochemistry, chemical engi-

(By Knaus.)

Fig. 3. Helmholtz.

neering, food chemistry, colloid chemistry. Where chemistry touches neighboring fields we have physical chemistry and biochemistry.

On the other hand, as we progress, we are perceiving much more clearly that, in the end, such subjects as physics and chemistry are both concerned with the same fundamentals. Men in these fields are all working with phenomena involving matter and energy in various forms and relations—interpreted ultimately in terms of atoms and molecules and their essential properties. This trend has proceeded now to the point where in some cases there is no real distinction between physicists and chemists. Similarly, as the biological and medical research men study living matter further, they find that they must use very much the same language of atoms and molecules and their properties as do chemists and physicists. Likewise they must use many of the same experimental

methods and tools. As we realize that the same principles underlie all the sciences, and that no sharp border lines exist, the unity of science becomes apparent.

It has gradually become possible to offer in colleges and universities a unified science program which embraces all the natural sciences. Such a thoroughly integrated program, intended for those who do not expect to specialize in science, presents many interesting possibilities. Much of the overlapping material can be eliminated, while the interconnections between the fields are emphasized. Thus the students, without specializing in one science, become acquainted with the chief branches of scientific investigation, with their dominant problems, concepts, and theories, and with the techniques of their experimental methods. The foundations of science education can thus be widened, leading to a clearer appreciation of the place of science in the social order.

WHAT DO WE MEAN BY SCIENCE?

Before we go far into any one field, we ought to have some understanding of what we mean by science. Thus far we have been using the term without attempting any rigorous definition. It is indeed very difficult to give a definition that will be as broad as we should like. Most of us see applications of a great deal of scientific knowledge in our everyday life, without even realizing it. The comparatively simple act of driving a car takes advantage of a vast number of scientific principles.

In a sense, science is the product of man's curiosity, of his imagination, and often of his pressing need. Man's desire to understand the world around him has been very strong, and his long search for ideas and for truth has produced not merely a dead set of facts, but the prologue of a living, fascinating drama. Our great body of accepted knowledge has slowly been accumulated in many ways—through simple observation and common-sense deduction, often by accidentally stumbling onto the "explanations" of phenomena, and, in the present era, through the highly developed technique of controlled and quantitative experimental investigation. Many human activities have played a part in scientific advancement—invention, religion, and, probably most important, curiosity.

Since arbitrary definitions are rather dangerous, perhaps we may better seek to understand what we mean by science through

considering the way in which a science comes into existence and grows. The beginnings of all science must lie far back near the dawn of human history. It was indeed a big step forward when some early man, perhaps with the aid of a limb broken from a convenient tree, discovered that he could easily move a rock too heavy to be moved alone, and thus invented the first lever. But while invention has played an important role, the real spirit of scientific thought goes much deeper.

We could learn a great deal about what science is from a study of one of its more limited parts, such as how man arrived at his first crude tools and from them developed more modern machines, or the development of geometry from the "rope stretchers" of Egypt.

In order to obtain a more comprehensive picture of the growth of a science, we shall follow, in the next two chapters, the gradual development of our present ideas about the solar system and the universe, which have grown out of man's first wonderment at the existence of day and night.

FOR STUDY AND READING

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SUMMARY

Science has profoundly influenced our modern world although the use of scientific methods is still in its early stages. These methods have been developed and applied in the natural sciences, but they must ultimately help solve social problems. Thus, leaders in fields other than the natural sciences need to understand science and its methods. Culturally, the appreciation of nature is as important as art and literature.

The distinctions between the sciences are largely arbitrary; all involve the same fundamental methods and tools. For those who do not intend to specialize in science, a comprehensive but unified college science program offers many advantages.

Science is a product of man's curiosity, his imagination, and often his pressing need. The meaning of science is best shown by the way in which it originates and grows, so it will be illustrated

in the following two chapters on the development of the science of astronomy.

QUESTIONS

1. In what respects is the study of science valuable to men who are not to be professional scientists?
2. No matter what field you enter, why can you be certain that the past and future developments in science will greatly influence your work and thought?
3. What are the sciences and how did the distinctions between them arise? Why has there been a trend toward specialization and sharply separated fields in science?
4. How much foundation is there for the statement that the same basic principles underlie all sciences?
5. If there has been a development of our civilization, wherein has science played a part?
6. In what ways is science likely to exert increasing influence on our social, industrial, and political order?

CHAPTER II

THE RISE OF A SCIENCE—THE HISTORY OF ASTRONOMY

EARLY MAN

Some hundreds of thousands of years ago the world must have seemed a wonderful and fearful place to primitive man who was gradually emerging as a thinking animal. We have no written records of the life of prehistoric man, but archaeologists and

(*American Museum of Natural History.*)

Fig. 4. Primitive painting of reindeer on the wall of a cave in France.

anthropologists have reconstructed much of his development, which probably began somewhere in southwestern Asia. The unwritten history left behind in the form of tools, weapons, skeletons, carvings, and ornaments provides a fragmentary picture of early human life and activity.

To early man the whole of nature was full of mysterious phenomena. Each morning a bright ball of fire climbed over the eastern horizon, bringing with it light and warmth, and pursued a course across the sky. Each evening the sun disappeared in the west, darkness descended, and the moon and stars appeared, shining with a fainter light. On the face of the earth all sorts of powerful agents were at work. Wind, rain, and lightning drove primitive man to

(*Brown Photos.*)

Fig. 5. Giant calendar dial at Stonehenge. Druid priests (1500? B.C.) timed ceremonies according to the alignment of the sun or stars on this dial.

shelter in caves. Possibly it was from fires started by lightning that man learned of the protection of fire against cold and darkness. He noticed that, as time passed, days gradually shortened and the nights lengthened, but that eventually the trend reversed, only to change again and again in rhythmic fashion. The weather changed slowly as this cycle of seasons progressed, and the miracles of plant and animal life followed the same cycle.

Magic and Religion. With so much before him that he did not understand, it is small wonder that man acquired many superstitions to "explain" natural phenomena. It was reasonable that the sun, the most prominent object in the sky and the cause of night and day and the seasons—the source of life itself—should be the principal deity for most early peoples. It was also logical that man, necessarily an egoist in his struggle for life, in addition to deifying natural phenomena should build gods in his own image and think of all nature as animated by the activities of superhuman beings. All early religions were thus based on anthropomorphism and animism.

(*Metropolitan Museum of Art.*)

Fig. 6. Early Babylonian records. Clay cylinder with inscription proclaiming the rebuilding of the Temple of the Sun God by Nebuchadnezzar II.

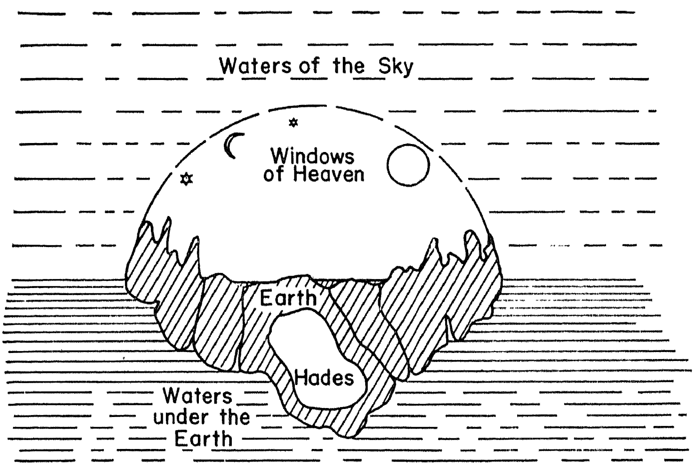
Long before the more trustworthy records of history began, man developed religions to satisfy his mystical nature. Some individuals became versed in magic; a class of professional priests and astrologers soon arose, interpreting the seen and unseen world to the people and predicting the future, doubtless often to enhance its own prestige.

The Beginnings of Observation. Very early in man's history, priests and astrologers apparently began to make some sort of systematic observations on the motions of the heavenly bodies. Since the sun god was the central figure in most religions, with the moon and planets and stars as lesser deities, it was inevitable that the priests study these heavenly bodies, though their motives might not have been entirely scientific.

The accumulated information about the heavens was passed on, at first through the medium of language and later through the early forms of writing. The interpretation of such information to foretell the future and impress the populace generally was decidedly pseudoscientific, but nearly all respectable sciences came from similar questionable beginnings. Indeed, that astrologers and their publications flourish even in this enlightened twentieth century is a sad commentary on the general state of popular understanding.

Babylonian, Chaldean, and Egyptian Civilizations. The contributions of these three ancient civilizations to science and culture are the earliest for which we have a reasonably complete record. Long

before 4000 B.C. the Babylonians and Chaldeans in the valleys of the Tigris and Euphrates, and the Egyptians in the valley of the Nile, had found equable climates and fertile soil where living conditions were sufficiently easy so that they had leisure to develop a



(*After Whitehouse.*)

Fig. 7. Ancient Semitic conception of the universe.

culture. The cuneiform writing on baked clay used by the Chaldeans was a great improvement over primitive hieroglyphics, and a considerable literature existed in that period. Such mechanical inventions as levers, saws, drills, windlasses, bows and arrows, and potter's wheel were by then in common use. The wheel and axle were used on Babylonian war chariots as early as 4200 B.C. Systems of weights and measures, so necessary to commerce, had been evolved, and time was measured by sun dials, water clocks, and by astronomical observation. The Chaldeans divided the day and night into 12 hours each.

Astronomy was held in great honor by the Chaldean priests who had studied the courses of moon and sun with some precision and are said to have predicted an eclipse. Catalogues of observations of fixed stars and "wandering stars," or planets, existed, as well as treatises on arithmetic and geometry. The basis for mathematics, which was to prove necessary to express the phenomena of astronomy and of all nature in clear, concise fashion, was being laid through the use of counting methods with a notation similar to Roman numerals. The Chaldeans divided the equator into 360 degrees, and also used the "Twelve Signs of the Zodiac." The

(*Metropolitan Museum of Art.*)

Fig. 8. Funerary papyrus of the Egyptian princess Etiu-ny. The judgment, where the heart of Etiu-ny is weighed against the figure of the Goddess of Truth.

sexagesimal number system probably arose from the belief of the oldest priest-astronomers that one year is just 360 days—that is, 12 lunar circuits of the heavens (months) of 30 days each. Thus $1/360$th of the entire solar circuit, believed to be the daily sun-step through the heavens, became the circular division now known as the degree.

Much of the early geometry had been worked out by the Egyptians. The regular inundations of the Nile obliterated men's land boundaries, so methods of surveying and measurement by men called "rope stretchers" were developed to settle boundary disputes after the floods. As early as 3600 B.C. the Egyptians had estimated the value of pi (π) from lengths of arc and diameters of circles, and obtained $3\frac{1}{7}$, although the Chaldeans used 3. Our present calendar had its beginnings in the Egyptian system of 12 months of 30 days each, with five extra holidays.

The relations in a right-angle triangle having sides with ratios 3:4:5 were recognized early and given mystical significance. Egyptian architects made use of this triangle to construct precise right angles, for example, on the bases of the pyramids. That the sum of the squares of the two sides was equal to the square of the hypotenuse in the 3:4:5 triangle was also known, but the generalization which might have been derived was not realized.

Most of the technical contributions of this period were thus of a practical nature: catalogues of facts, mechanical inventions or systems, and methods having commercial application. There was some progress in observation of natural phenomena, but no real attempt had been made to formulate the behavior of nature through general physical descriptions.

DAYS OF THE WEEK WERE NAMED AFTER MEMBERS OF THE SOLAR SYSTEM

	English	Old Norse	Anglo-Saxon	German	Latin	French	Spanish
Sun..........	Sunday	Sunnudagr	Sunnandæg	Sonntag	dies Solis	Dimanche	Domingo
Moon........	Monday	Manadagr	Monandæg	Montag	Lunae dies	Lundi	Lunes
Mars.........	Tuesday	Tyrsdagr	Tiwesdæg	Dienstag	Martis dies	Mardi	Martes
Mercury......	Wednesday	Othinndagr	Wodnesdæg	Mittwoch	dies Mercurii	Mercredi	Miércoles
Jupiter.......	Thursday	Thorsdagr	Thunresdæg	Donnerstag	Jovis dies	Jeudi	Jueves
Venus........	Friday	Friggdagr	Frigedæg	Freitag	Veneris dies	Vendredi	Viernes
Saturn........	Saturday	Seternedagr	Sæterndæg	Samstag	dies Saturni	Samedi	Sábado

SCIENCE IN GREECE

Somewhere about 800 to 600 B.C., the people, predominantly of Aryan origin, who had displaced the earlier inhabitants of the Greek peninsula and the Ionian coast of Asia Minor began to develop a distinctive culture. In the course of a few hundred years they were to make what were probably more vital contributions to social and intellectual life than any group before or since.

Here at last we see the brilliant dawn of real science among a people who, because of the genial climate, the fertile soil, and the abundant leisure based on a slave system, were able to achieve freedom of thought and to break away from tradition and superstition. Here it became possible to think about physical phenomena in a rational, objective manner. Science was no longer pursued as a tool or as part of the lore of priesthood, but for its own sake in a search for truth. However, there were, as we shall see, many shortcomings in Greek science.

Ionian Thought. Greek science first began to develop in Ionia. Thales (640–546 B.C.),[1] a native of Miletus, was probably the first Ionian thinker of note, and is recognized as the founder of Greek astronomy. Although little is known of his actual work, it is clear that the break from mysticism toward realism had already begun in the many phases of nature in which Thales was interested. Among

[1] Vital statistics concerning the ancients are frequently open to dispute.

the discoveries credited to him is that of electricity from electrified amber—*elektron.*

Thales learned much about astronomy and geometry from travels in Egypt. There he is supposed to have devised a method for measuring heights of pyramids from the lengths of the shadows cast along the ground. First to teach Greek sailors to navigate with the polestar as a guide, Thales is also supposed to have understood that the four natural seasons constitute a cycle marked by longest, average, shortest, and average periods of daylight. He gained much prestige through his prediction of an eclipse which, by modern calculations, probably occurred in 585 B.C.

A number of other Ionians made contributions to art, poetry, and science. Leucippus and his pupil Democritus (about 465 B.C.) we shall meet later, for Democritus set forth the theory, revived many years later, that all matter is composed of indivisible atoms in rapid and continuous motion.

The Pythagoreans. Pythagoras (582–500 B.C.) emigrated to southern Italy, and there so stimulated a group of intellectuals that an active, continuous study of many fields, ranging from ethics and music to astronomy and mathematics, was maintained for several centuries.

The "harmonies of the universe" deeply impressed the Pythagoreans. Numbers and number arrangements were given mystical significance. The ideas of this group were strange mixtures of partially correct concepts and the mystical legends of their day. For the first time, however, mathematics and geometry were pursued in an abstract, intellectual fashion. Arithmetic was expanded, and many theorems of geometry were developed on the basis of a few postulates and axioms. The familiar Pythagorean theorem, that the sum of the squares of two sides of a right triangle is equal to the square of the hypotenuse, was discovered, thus generalizing the early Egyptian observation about the 3:4:5 triangle.

The Pythagoreans pictured the universe with the earth at the center, encircled by spheres, one for each planet and one for the fixed stars. Each sphere had its characteristic tone. Harmonic relations between these tones were symbolized as the "music of the spheres." The Pythagoreans believed that, because the universe is harmonious, all nature could be expressed in terms of numbers. This concept of the universe as a geometrical, mathematical model

opened up many new avenues of thought which led to the very basis of modern astronomy and modern physics. At the same time, it postulates the idealistic philosophy of a universe of perfection which permeated all later Greek thought.

(*From Arrhenius.*)

Fig. 9. Early Greek map of the world.

Greek Thought Flourishes. Socrates and Plato, outstanding intellectuals of the group at Athens during the fifth and fourth centuries B.C., were interested mainly in humanism and in political and social philosophy, and gave very little to science. Aristotle (384–322 B.C.) exerted an enormous and lasting influence on Greek science. He so overshadowed his contemporaries and those who followed that, perhaps unfortunately, his ideas dominated the philosophy and the science of the world for some 20 centuries. He was interested in every field of thought. His rich knowledge of the past and the tremendous amount of information accumulated from his own travels and through the students working under him enabled him to systematize in encyclopedic fashion the thought of his time. The importance of experiment in the natural sciences seems to have been sensed by Aristotle, who may even have carried on some biological experiments. Unfortunately, however, preconceived theories all too often took precedence over experimental procedure, especially in the fields of physics and astronomy.

Aristotle's eight books about physics and astronomy contain many nearly correct ideas, but on the whole they are so metaphysical and full of errors that they are of doubtful value. With his voluminous, authoritative style and his continual search for the "nature" of things, it is not surprising that his works were later to appeal strongly to the medieval mind.

In mechanics, his concepts of levers, pulleys, and of other simple machines were fairly good. However, he believed that bodies fall with speeds proportional to their weights, when offered equal resistance by the air or other medium in which they move. His prestige was so great that this idea was generally accepted, and the whole science of moving bodies was consequently retarded until Galileo's experiments some 19 centuries later. Yet a simple experiment, performed by dropping two unequal weights at the same time, could easily have settled the whole matter!

Aristotle's model of the universe borrowed much from the observations and thought of his predecessors. Four elements, earth, water, air, and fire, composed the world, earth being nearest the center and water next, while air and fire formed the atmosphere. Straight-line motion was supposed to be a natural property of these terrestrial elements. The celestial bodies were of a fifth element, *aether*, with natural circular motion. The universe was considered to be spherical, because the sphere was the most perfect form; the earth was spherical for the same reason, and this was further proved by the curved form of the earth's shadow on the moon during a lunar eclipse. That solar eclipses were caused by the spherical moon coming between the sun and the earth was understood by Aristotle.

The size of the earth was considered "not large in comparison with other stars." The circumference of the earth was estimated to be 400,000 stadia—about 46,000 miles—but this value was probably not original with Aristotle. Curiously enough, although a spherical earth was one of the accepted concepts of the Greeks in 300 B.C., it was later almost forgotten until about A.D. 1490, when Columbus and others brought about its reacceptance.

Aristotle firmly insisted on the geocentric system of the universe, on the premise that the earth *must* be the center of the universe, since it was created expressly for this superior being—man. The apparent motion of the planets was explained by a scheme that may be traced back to Pythagoras' idea in which the planets

were assumed to be fixed on invisible crystalline spheres. The motions of the spheres were described geometrically by Aristotle in terms of "epicycles": the type of curve traced by a point on the circumference of a small circle the center of which follows

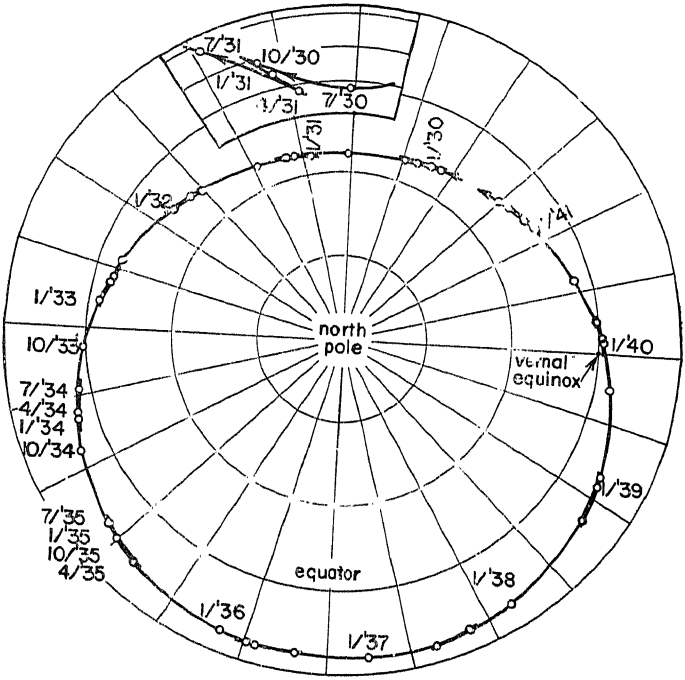


Fig. 10. Map of apparent path of Jupiter—July, 1929, to April, 1941. The section from July, 1930, to July, 1931, is enlarged to show "retrograde motion."

a larger circle (see Fig. 11). He argued, with some justification, that the absence of any apparent displacement of the stars proved that the earth had no orbital motion.

On the other hand, a number of men—among them Aristarchus of Samos—had already pointed out the equal plausibility of the heliocentric theory. Aristarchus held that the sun was the center of the solar system and that the planets, of which the earth was one, revolved about the sun with different periods. The alternation of day and night was thus presumed to be due to the rotation of the earth.

Actually, the accuracy of astronomical observation was not great enough at that time to decide between the two points of view.

Aristotle's geocentric theory was just as well founded as the heliocentric theory. The question was not to be settled until some 20 or 21 centuries later, in the modern era of precision astronomical measurements.

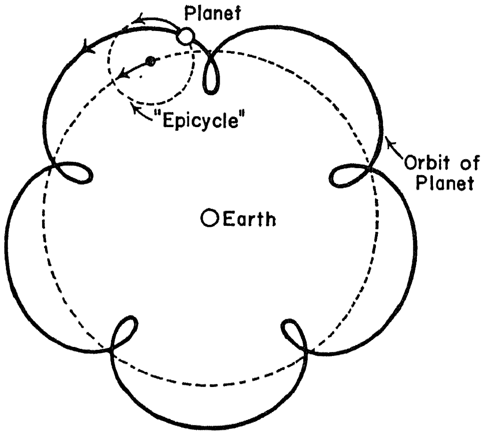


Fig. 11. Path of planet according to Aristotle.

The Weaknesses of Greek Science. From what we have seen, it is clear that Greek science had several fundamental weaknesses. The Greek scientists assumed that the universe was "perfect" and thus readily susceptible to complete analysis by the human mind, provided the proper premises be taken. More serious, however, they neglected to perform experiments to test their hypotheses and the deductions from their theories.

The assumption of a universe of perfection led the Greeks to build elaborate pictures of the whole universe, step by step, through reasoning based on poorly founded hypotheses. It is true that they used the method of ***inductive reasoning,*** in which one arrives at a general conclusion by considering a number of observed facts. The Greeks, however, did not make many observations, and indeed when some observed fact disagreed with a theory they often preferred to disregard the fact in order to maintain the perfection of their ideas. Inductive logic and reasoning is one of the most powerful tools of modern science. Now, however, we do not hesitate to discard any theory that does not agree with the observed facts.

The Greeks also used the method of ***deduction,*** in which one arrives at a specific case from a general principle by the use of connective reasoning. This method was especially successful in the

case of geometry, but, of course, it can be no better than the axioms on which the reasoning is based.

The anthropomorphic conception of the universe, with man and the earth the center of all things, led the Greeks to approach the problems of nature from an unsatisfactory point of view, the difficulties of which present serious problems even today. Man's mystical nature has always led him to seek for an ultimate answer to "why" the universe exists, and "why" phenomena in nature occur. However proper this question may be, this search for the ultimate "why" has not proved to be a satisfactory basis for real progress in science, where great advance became possible only when we stopped asking "why" and instead asked ***"how."*** There is a tremendous philosophical difference between these two outlooks. It is as impossible to answer the question, "why?" about a fundamental idea as it is to establish an absolute truth.

The differentiation between the old and the new in science and civilization is largely this distinction between the request for authority (why?) and the search for descriptions in terms of familiar processes (how?). It was not until some 19 centuries after Aristotle that a few men were able to break away from the earlier approach and begin to experiment fearlessly in order first to find the facts of nature and then to "explain" or, more correctly, to describe these facts in terms of one another.

The Greeks did appreciate the value of experimentation, but they made so little use of it that there was no sound basis for the pretentious scope of their theories. Theirs was largely "arm-chair reasoning." Careful investigation of nature requires a great deal of manipulation, but it was beneath the dignity of true Grecian aristocrats to soil their hands in manual labor.

Science in Alexandria. After the subjugation of the Mediterranean peoples by Alexander in 332 B.C., the chief activity of Greek science was transferred to Alexandria, the new Egyptian capital, where it remained for 700 years. The Museum (Seat of the Muses), with its great library and lecture halls, flourished as an important intellectual center.

Here Euclid organized the contemporary knowledge of geometry into a form that is still widely used. His system of strict conformity to a definite logical sequence, starting from fundamental axioms and postulates stated in advance and progressing through

step after step of reasoning to the final conclusion, set a new standard in logic and represents a milestone in the growth of mathematics. Euclidean geometry served as the essential foundation for all the subsequent astronomical and physical considerations of space and time.

Archimedes—One of the First Great Scientists. One of the greatest of all Greek scientists, Archimedes (287–212 B.C.), was centuries ahead of his time in many fields. Mathematician, physicist, engineer, and inventor, his approach toward physical problems was surprisingly modern—quite different from that of most of the Greek school. He was one of the first to make systematic investigations of natural phenomena and to use an unbiased objective point of view.

Many of his books have been preserved. They include numerous contributions to geometry, dealing with the properties of spheres and cylinders, the measurement of spirals, conoids, and spheroids, and his famous work on floating bodies. He successfully attacked many problems by the essentially modern method of successive approximation, quite contrary to the spirit of Euclid. He used summation principles which anticipated integral calculus, and among other things arrived at an accurate value of π. In his attempt to calculate the "number of grains of sand which would fill the universe," he used methods comparable to the modern exponential system, and arrived at an upper limit of 10^{63} grains.[1]

Archimedes laid the basis for much of mechanics, especially that part which deals with bodies at rest. From a firm experimental basis, he formulated many general laws and mathematical proofs concerning the composition of forces, centers of gravity, inclined planes, pulleys, laws of fluids, and specific gravity problems. Archimedes was in many ways the first real applied physicist or engineer, combining fine theoretical background with exceptional practical insight. His work on balances, levers, worm or endless-screw gears, and machines in general was superior. His famous water screw for pumping water is still used for irrigation purposes in Egypt. Simple gear systems were devised to launch ships, and he even boasted that, given the proper lever system, he could move the earth.

As military engineer under King Hiero, Archimedes' great technical skill was a factor in the defense of Syracuse against the

[1] Short notation for 1 followed by 63 zeros.

Romans. His various war machines, among them devices for projecting stones and other materials, proved very effective. Archimedes, however, was interested chiefly in pure science for its own sake and regarded the engineering phase as secondary.

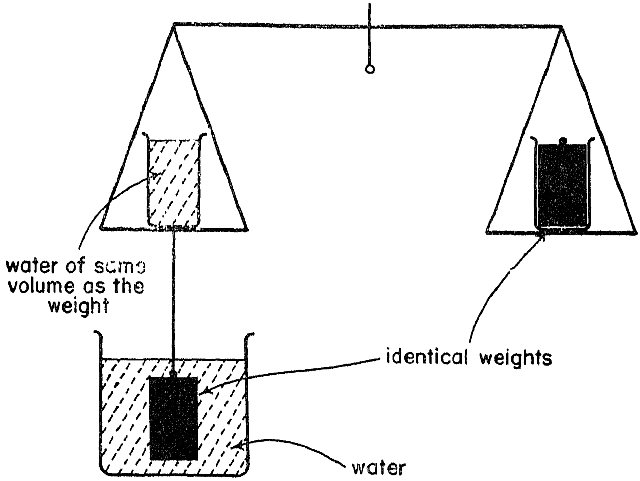


Fig. 12. A principle discovered by Archimedes. The weight "lost" by an object when it is immersed equals the weight of fluid which it displaces. The object on the right is exactly balanced by an identical object immersed in water on the left plus the amount of water which would occupy the same volume as the object. Legend says Archimedes arrived at this principle when asked to determine the amount of gold in King Hiero's new crown.

Although he was not primarily an astronomer, Archimedes' experimental point of view and strikingly original work in mathematics and mechanics played a vital role in the progress of the science of astronomy. He constructed a mechanical model of the universe, similar to a modern "orrery," with a celestial sphere of stars and a moving planet system. It was preserved for many years in Rome.

Astronomy in Alexandria. Astronomy was an active field in the Alexandrian school. The circumference of the earth (assumed to be a sphere) was estimated with some accuracy by Eratosthenes (276–194 B.C.). He understood that a vertical object at Syene, Egypt, some 5,000 stadia—about 625 miles—south of Alexandria threw no shadow at noon of the summer solstice, June 21, while at Alexandria he observed that the angular distance of the sun from the zenith (directly overhead) at that time was about one-

fiftieth of the "circumference of the heavens." This gave about 250,000 stadia (probably close to 29,000 miles) as the earth's circumference, not very far from the modern value of 24,900 miles.

Eratosthenes' measurement of the variation of the sun's

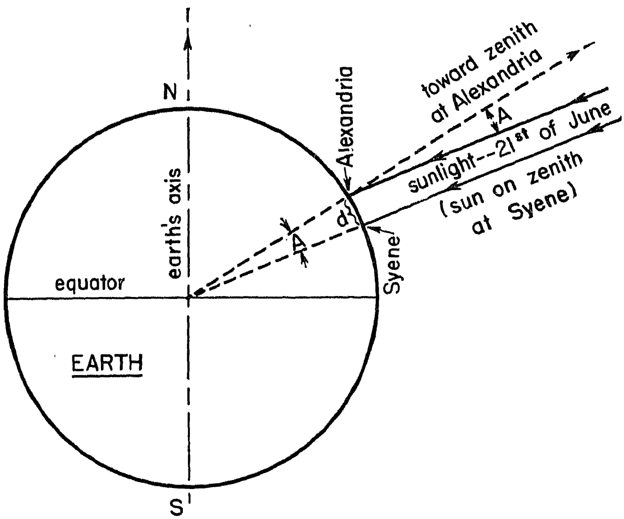


Fig. 13. Eratosthenes's measurement of the earth's circumference. From the distance d and the angle A he was able to calculate the circumference.

"zenith distance" as he changed his location suggests how astronomical measurements were to be more generally used to determine positions on earth as an aid to navigation. Although accurate methods were not achieved until comparatively modern times, the hope of removing some of the guesswork from sailing beyond the sight of land was a continuous spur to astronomical investigation.

A considerable school of astronomical observers developed at Alexandria, where systematic observation with graduated instruments was carried on over a long period. The body of experimental data thus accumulated became the basis for the brilliant work of Hipparchus and later of Ptolemy.

Hipparchus. The works of Hipparchus are mostly lost, except as carried on by his disciple Ptolemy and recorded in the famous *Almagest.* Hipparchus, who died about 125 B.C., was so impressed by the sudden appearance of a new star in the supposedly changeless firmament in 134 B.C. that he set out to make an improved star catalog to serve as the basis for future investigations. He included

a critical revaluation of the work of earlier observers, and instituted a long series of careful observations with the best available instruments. About 1,080 stars were included in his catalog. He not only gave the position and the celestial latitude and longitude

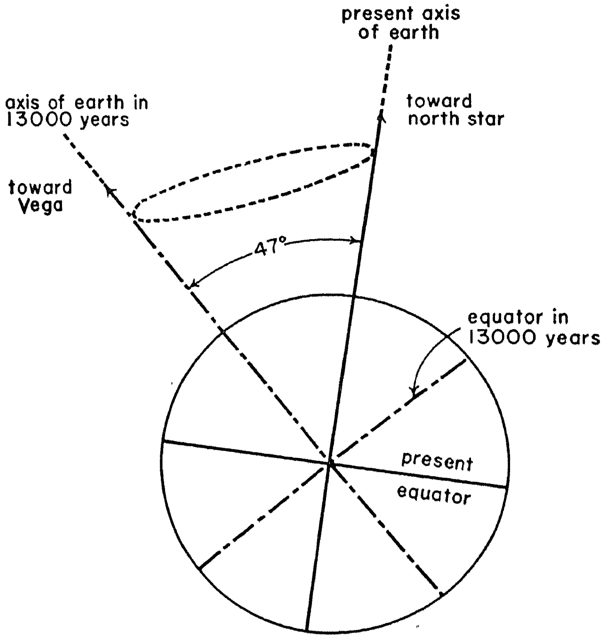


Fig. 14. Hipparchus discovered the precession of the earth's axis. Known also as the precession of the Equinoxes. (See page 28.)

of each star, but also classified the stars (according to their relative brightness) into six different magnitudes. This work set the standard until Tycho Brahe's time, many hundreds of years later, and Hipparchus' designations for the major constellations are still used today.

Hipparchus was able to improve considerably the calculations of the orbits of the sun and moon, using the geocentric basis. The order of the planets was supposed to be: Moon, Mercury, Venus, Sun, Mars, Jupiter, and Saturn. The calculations agreed about as well with observations as the experimental accuracy permitted, but Hipparchus keenly realized the need for more precise data before any definite model of the solar system could be settled upon. The length of the year was determined to within about six minutes, as 365 days, 5 hours, 55 minutes—slightly less than 365¼ days.

The most remarkable discovery credited to Hipparchus was the precession of the equinoxes. Comparison of his observations with those of 150 years earlier showed a change in the position of some stars of about two degrees. Hipparchus had the insight to interpret this as corresponding to a slow rotation of the earth's axis (a precession of the axis similar to that of a spinning top) so that the celestial pole describes a circle in a period which modern figures show to be about 26,000 years.

Hipparchus also laid the foundation for trigonometry and probably was responsible for the introduction of latitude and longitude for indicating positions on the earth. These concepts were essential to the attempt to apply astronomical methods to navigation. After Hipparchus, intellectual activity declined until the time of Ptolemy in the second century after Christ.

The Ptolemaic System. Some 260 years after Hipparchus, the Alexandrian, Claudius Ptolemy, gave Greek astronomy its most complete formulation in the *Syntaxis*, better known from its Arabic translation as the *Almagest*. Ptolemy, aided by more refined instruments, carried forward the program of observations of stars and planets begun by Hipparchus, and revised the catalog of stars. Among the instruments then in use was the "Ptolemaic rule," a rod with sights, pivoted on a vertical rod and arranged to measure the altitude and the meridian angle of an astronomical body. The astrolabe, a graduated circle and an index equipped with sights for measuring vertical angles, was also extensively used, as well as various other quadrant and circle devices. Ptolemy still measured time by the flow of water, although more accurate methods were beginning to appear. He also studied sound and optics and investigated many phenomena connected with the refraction of light.

Ptolemy's concept of the universe differed little from that of his predecessors. He accepted the geocentric theory and attempted to prove that the earth must be the center of the heavens by numerous arguments, such as: "If the earth were not the center, one side of the heavens would appear nearer to us than the other and the stars would appear larger there."

This failure to realize that the distances to even the nearest stars were enormous compared to the distances in the local solar system continued to cause misconceptions. Ptolemy, however, understood

that the earth itself must be considered virtually a point in comparison with the distances to the stars, since the stars appeared the same, no matter from what position on the earth they were viewed. He argued that the earth could have no motion of translation,

(*Courtesy of The Sky.*)

Fig. 15. Ptolemy holding a "Ptolemaic rule."

because its center must be the fixed reference point, the "center of the heavens," to which all heavy bodies descend. Ptolemy held that objects thrown into the air would be left behind if the earth moved, or would be hurled outward if it rotated on its axis. Consequently, he denied the possibility of all terrestrial motions, even though he agreed that admission of the earth's rotation would simplify many problems. It is only fair to admit that until Newton introduced the "law of gravitation" these ideas were very plausible.

By the use of ingenious methods of interpolation and approximation, Ptolemy extended the method of calculation of arcs from chords until the accuracy approached five decimal figures. He arrived at a value for π of 3.1416. He improved Hipparchus' description of the motion of the sun and moon in terms of eccentrics and epicycles, often attaining an accuracy of 10 minutes of arc. Tables were calculated so the moon's position at any desired time

could be determined. Although calculations of the sun's size and distance were badly in error, estimates of the moon's radius and its distance from the earth were quite accurate.

Ptolemy's chief astronomical contribution, however, was a description of planetary motion. He was still bound by the Aristotelian dictum that celestial objects could follow only circular paths. In order to describe, within the observational limits, the apparent retrograde motion of the five planets or "wandering stars," it was necessary to combine two circular motions in the fashion shown in Fig. 16.

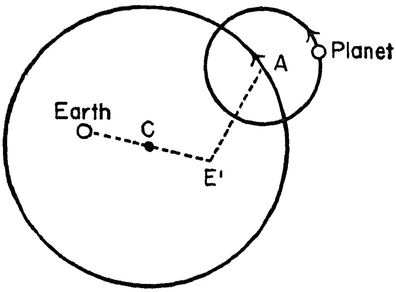


Fig. 16. Path of a planet according to Ptolemy. The planet follows an "epicycle" the center of which (A) moves uniformly about E′.

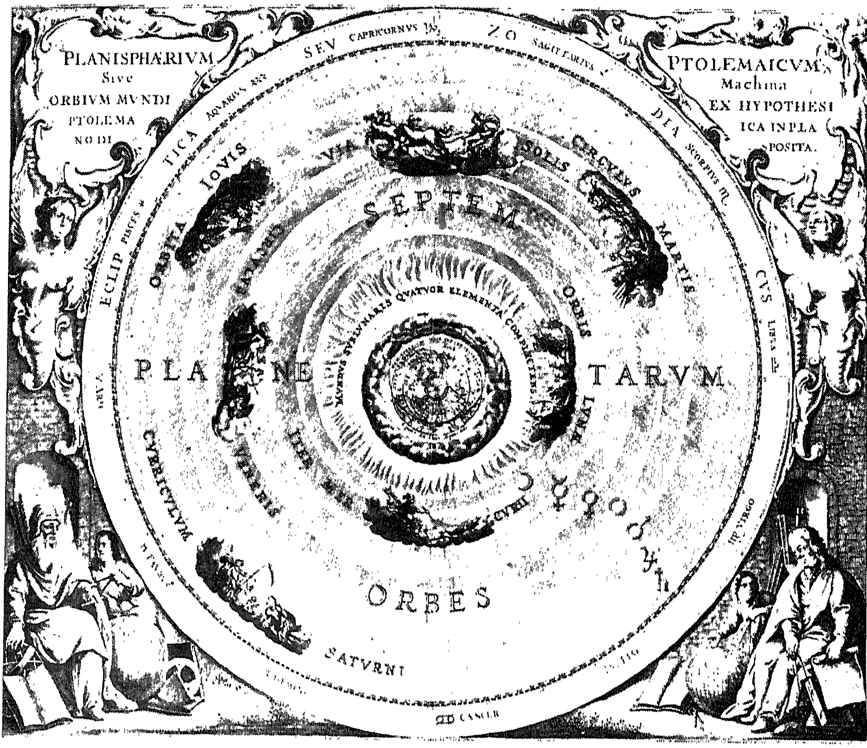
For some 1,400 years Ptolemy's picture remained the foundation for theoretical astronomy. Today it seems strange that as ingenious a mathematician as Ptolemy did not realize that all this complication could be greatly reduced by assuming the heliocentric system. However, he apparently considered his scheme to be but a geometrical model of the motions and not necessarily a "true" description. Furthermore, the concepts of relative motion which were required to develop a heliocentric system were not well understood. Taking into account the state of knowledge at the time, then, Ptolemy's work represented an admirable achievement and his scheme showed a great advance over the mystical fixed spheres of Pythagoras and Aristotle.

RESULTS OF CALCULATIONS BY HIPPARCHUS AND PTOLEMY COMPARED WITH MODERN VALUES

(The earth's radius is used as the unit of distance.)

	Radius of sun	Distance to sun	Radius of moon	Distance to moon
Hipparchus	12	2550	0.29	60
Ptolemy	5.5	1210	0.29	59
Modern	109	23,000	0.273	60.3

Greek Science Declines. After Ptolemy, little was accomplished in astronomy or in any of the other sciences for some ten centuries. By A.D. 300 the political decline of Greece had proceeded so far that



(*Courtesy of The Sky.*)

Fig. 17. Ptolemy's conception of the universe according to an eighteenth century atlas.

the Greek world had become largely engulfed in the Roman tide. Under Roman autocracy and Christian hostility, the intellectual and cultural background that made Greek science possible had gradually disappeared. The writers in this period were mainly commentators. The virtual destruction of the Alexandrian libraries in A.D. 415 marked the end of the Grecian epoch.

The torch of science was to be kept burning dimly, principally by the Arabs, until in later ages it was once more fanned to ever-increasing brilliance in western Europe. Greek science had had its day. Although weaknesses existed, as has been pointed out, the Greek thinkers were mainly responsible for the development of a truly scientific spirit from a heritage of little more than a knowledge of the practical arts and a mixture of superstitions. With them began the spirit of free inquiry, of rational interpretation, of generalization from observation and experiment. The claim that scientific development in Greece had run its entire natural course is

difficult to accept, for under more favorable political, economic, and military conditions Greek thought might well have been able to overcome its weakness and to have yielded new and greater achievements.

THE FOURTEEN-CENTURY INTERIM

Science in the Roman World. Rome rapidly extended her political and economic domination from Britain to India and south into Egypt so that, from about the second century B.C. to the fifth century after Christ, she controlled civilization.

That the Romans showed a lack of real interest in science or scientific research is one of the most striking facts of history. As their influence extended over the various countries and peoples, work in science progressively declined. Considering their great genius in military fields, politics, and engineering, as well as their contributions to literature, oratory, and history, the complete apathy of the Romans toward pure science and intellectual life is indeed surprising. The individuals who maintained some active interest in science, such as Lucretius (98–55 B.C.) and Pliny the Naturalist (A.D. 23–79), were rare; most of them wrote commentaries on the old Greek treatises, summarizing knowledge already existing.

Astronomy reverted to astrology. Mathematics and the physical sciences languished. One important change, from an astronomical standpoint, was the great improvement in the calendar. By 47 B.C. the accumulated error engendered by maladministration of the calendar amounted to about 85 days. Julius Caesar, advised by astronomers, instituted the so-called Julian calendar, with a year of 365 days but with an additional day in February every fourth year. This compensated quite accurately for the actual length of the year, which is slightly less than $365\frac{1}{4}$ days. It is somewhat ironical that this well-conceived calendar was not fully effective for a long period because a misinterpretation of the regulations made every *third* year a leap year.

The Roman Empire and the Republic emphasized the extension of military and political domination, the expansion of trade, and the engineering phases of science. Greek science and culture were used only as they yielded practical results, so that original thought, the spirit of free investigation, and experimentation declined almost to the vanishing point. Roman domination brought an age of intellectual poverty.

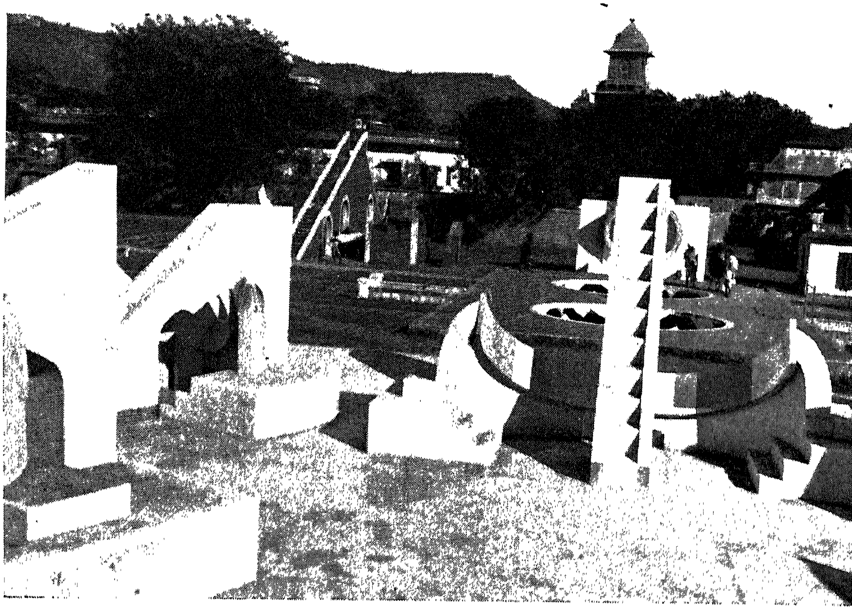
Disintegration of Roman Civilization. A new period in the history of science began with the downfall of the highly developed Roman civilization. The Empire was weakened by internal corruption, overexpansion, political dissension, and an inadequate economic system. The social order was top-heavy, and the large underprivileged groups were kept in order by a military dictatorship.

The Christian religion first found its great strength among the submerged masses, and the consequent spiritual liberation and unification of the lower classes became one of the most important factors in weakening the power of the aristocrats. The invasion by the barbarians from the north—the Goths, Huns and Vandals—and by the Arabs from the east completed the disintegration of Imperial Rome.

Science at Its Lowest Ebb. In the state of chaos and disruption which accompanied the breakup of the Roman Empire, science was almost forgotten. The semicivilized nations were not yet ready for scientific work. Early Christianity's unfortunate antipathy toward intellectualism made it difficult to pursue knowledge for its own sake. Study of the soul and the word of the prophets was its major aim. All Greek thought was considered by the Christian Fathers to be immoral, pagan, or degenerate. The sun of science was rapidly sinking, and by the fifth century the intellectual darkness of the Middle Ages was complete.

In the western Mediterranean the great centers of learning disappeared, and the University at Athens and other eastern schools were closed by Justinian in A.D. 529. With emphasis placed entirely on the spiritual and nonworldly, there was no place for the study of nature or of man. There remained only theology for the pursuit of the educated from about A.D. 450 to 1450. Almost 14 centuries elapsed between the publication of Ptolemy's *Almagest* and the death of Copernicus in 1543, and during this period, about twice as long as that from Thales to Ptolemy, no important discovery in astronomy was made. Here and there during that time, however, a slight continuity of learning was maintained in the West in spite of great discouragement.

Arabian Science Rises. At the time of the founding of Mohammedanism (about A.D. 622), the Western world was so disorganized that the Arabs were soon able to conquer all the country south of



(*Donald Good.*)

Fig. 18. Observatory of the prince-astronomer Jai Singh at Jaipur, India.

the Mediterranean and much of Spain. Such a vigorous group as the Arabs naturally included men of intellectual power, interested in thought and nature. With the wealth and leisure resulting from their conquests, the essential conditions for scientific progress were established, and considerable freedom of thought was possible. During the long period of chaos in Europe the Arabs served as the custodians of Greek knowledge.

Centers of learning were established in such cities as Bagdad and Jerusalem and about A.D. 800 at Cordova, Toledo, and Seville in Spain. From the Hindus, much was learned of algebra and arithmetic, and the so-called Arabic (really Hindu) system of numerals was adopted. This system included the symbol zero, and also the principle of number positions that we now use. This simple new notation permitted a rapid expansion of mathematics, which had been impossible with the cumbersome Roman numerals. Translations from the works of Galen and Hippocrates were studied, and interest in medicine flourished. The influence of this period is illustrated by numerous scientific terms of Arabic origin, such as algebra, zenith, and almanac. Since astronomy was in great favor, well-equipped observatories were built at Damascus, Bagdad, and Malaga, and a continuous program of accurate observations was

undertaken. Star catalogs were thus kept up to date. Also, several astronomical works such as the *Almagest* were translated.

About A.D. 1000, Alhazen made considerable progress in optics. He studied the laws of reflection and refraction at plane and spheri-

(*Bausch and Lomb.*)

Fig. 19. Alhazen studied the refraction of light and disputed the ancient belief that visual rays emanated from the eye.

cal surfaces and worked with parabolic mirrors which later were to become important to reflector telescopes. His description of the human eye was remarkable, and he maintained that vision was due to rays coming from the object, not the eye. He concluded that the stars were self-luminous and did not receive their light from the sun.

Although they were patient and accurate observers, calculators, and translators, the Arabs made but few fundamental contributions to science. Their most valuable function was to keep alive interest in science and to preserve the discoveries of their Greek predecessors until the new dawn of science.

Europe in Transition. In western Europe, the struggle to salvage the wreckage of Roman civilization and reestablish a more stable social order was long and bitter. From the Empire evolved an enormous number of constantly warring feudal states, in which the masses of people had little or no freedom. In this period of confusion, of warfare, and of materialistic lust for power, the early church exerted more and more influence in binding all the peoples together. In the West, the Roman Church, under the leadership of the Popes, set up a formal centralized organization and extended its sway until, by about A.D. 1200, it ruled the world temporally as well as spiritually.

Education in medieval society was practically nonexistent. The requirements for self-preservation left little time for pursuit of learning. The influential church leaders, moreover, believed that the necessity for support by the masses made it imperative that the people be taught only enough to strengthen the church and to maintain faith in it. Independent thinking was strongly discouraged.

Decline of Feudalism and Growth of Commerce. The unification of many feudal states and the control over much of Europe gained by the military genius Charlemagne (742–814) led toward reestablishment of education. Charlemagne became interested in learning, and founded a school at his court to which eminent scholars were invited. He also insisted that ecclesiastical authorities establish schools in all abbeys throughout his dominions.

An important trend in Europe began about A.D. 1000 with the growth of the independent city states. A few cities succeeded in breaking away from feudal control to form semidemocratic community organizations. When well fortified and well situated, these city states became centers of trade and commerce where strong artisan and merchant classes developed.

The coastal city states were favorably located to develop foreign trade, and thus free intercourse between various peoples was encouraged. A feeling of economic solidarity between communities with common language and interests prompted the growth of nationalism. The contacts with Spain, Constantinople, and the Arabian East brought an interchange of learning as well as of articles of commerce. With prosperity came more freedom and leisure. Education became freer, and an intelligent and better educated public was in the process of formation. Scholars could exist now more or less independent of ecclesiastical organizations, and these scholars were to be largely responsible for the Renais-

sance. In such an atmosphere, science could once more begin to grow.

Science and Scholasticism. The monasteries and abbeys still served as the main intellectual centers in this period. Greek and Arabian manuscripts were preserved in them, studied, and translated into Latin. The reawakening of interest in Greek philosophy brought Aristotle into especial prominence, so that eventually his works dominated and colored the whole thought of the times. Aristotle's philosophy of government by aristocracy and his dogmatic pronouncements on science appealed strongly to the groups that were primarily interested in establishing a logical basis for a Christian dialectic. His doctrine that the earth is the center of the universe and that man is the center of creation agreed well with medieval Christian preachings.

There appeared many able intellectuals such as Thomas Aquinas (1227–1274), but the emphasis on Aristotelian authority prevented much progress in science. Little originality could exist, and the triviality of much of the discussion was ridiculous. As an example, one question actually debated was the number of angels that could dance on the point of a needle! Argument based on authority was preferred to facts based on observation. Even in the new universities which arose at this time, such as the University of Paris, which was founded in the twelfth century, and later ones in Bologna, Padua, Oxford, and Cambridge, complete adherence to Aristotle was of prime importance. Until the fifteenth century, scholasticism was far from a study of nature; it was a study of authorities.

New Thought from Within. Naturally, within such a system, a few men of independent mind rebelled against the limitations on free inquiry—men such as Peter Abelard (1079–1142), Albertus Magnus (1193–1280), and Roger Bacon (1214–1294). Some of them, who were tactful, were able to pursue their work within the system. Others were persecuted and even burned to death, although much of the persecution may have been due as much to their personal tendencies to make enemies as to their zealous insistence on heretical ideas.

Roger Bacon, a Franciscan who was one of the first to rebel against authority, insisted that experimentation and mathematical reasoning were the only satisfactory methods to advance science. Bacon had a considerable knowledge of optics but his chief con-

tribution was a new attitude of mind. For some of his less tactful remarks, he spent 20 years in prison.

Renaissance—Rise of Independent Thought. After reaching a peak about A.D. 1200, the power of the church slowly declined. The

(*Yerkes Observatory.*)

Fig. 20. Earth-lit "old moon in new moon's arms."

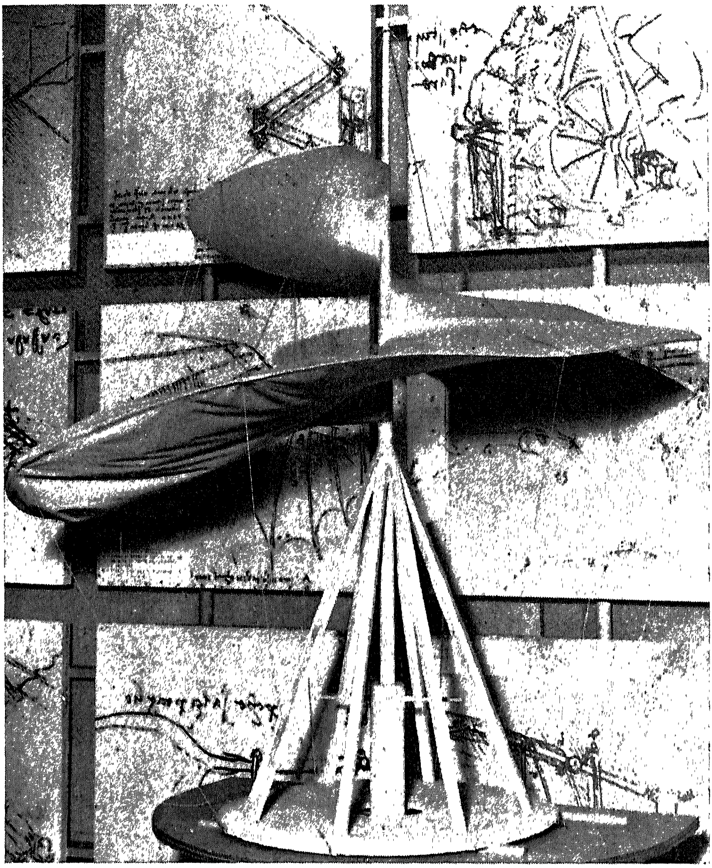
growth of semidemocratic city states and of nationalism, and the resulting conflicts with aristocracy and royalty, combined to reduce ecclesiastical authority.

Increasing numbers of independent thinkers began to come from the artisan and merchant classes. Outstanding among them was *Leonardo da Vinci* (1452–1519). Da Vinci made few contributions to astronomy, but he did give the correct explanation for "earthshine." This faint glow from the part of the moon in the earth's shadow at the time of the new moon he attributed to light reflected to it from the earth. He did brilliant work as a painter, physicist, mathematician, engineer, and physiologist. Da Vinci was a firm advocate of experiment and had considerable interest in mechanics, especially levers, inclined planes, and the equilibrium of forces. His daring imagination even led him to design a flying machine similar to modern helicopters.

Discovery of Printing. The birth of the art of printing was of far-reaching consequence in all intellectual activity. This development was long in coming, for it necessitated the simultaneous

ʳolution of the proper paper and suitable ink, and the invention movable type and press. The first printed Bible, attributed to utenburg, came from the presses in Mainz about 1456.

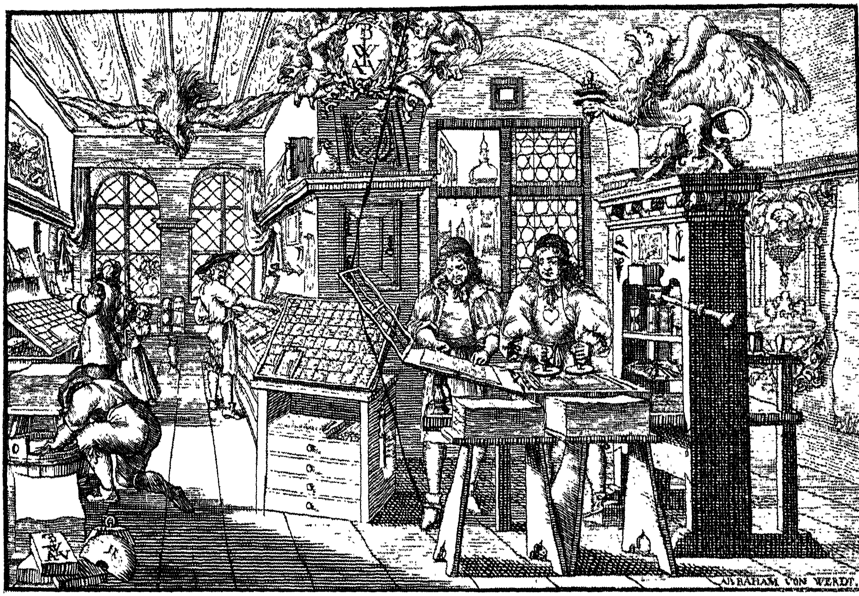
The possibilities of printing for the wide dissemination of ideas



(*New York Museum of Science and Industry.*)

Fig. 21. Model of heliocopter designed by da Vinci to rise vertically from the ground. Like most of da Vinci's multitudinous designs it was ingenious but never tested. Note sketches of other apparatus.

ong the poor as well as the rich were immediately appreciated. 1500 there were probably several hundred presses in operation l a great many volumes had been printed. Printing was a tre-ndous aid to the spread of learning, and it was of particular ue to science, since knowledge which previously reached few ld rapidly be made available to all. The famous presses at remberg published almanacs of astronomical information,



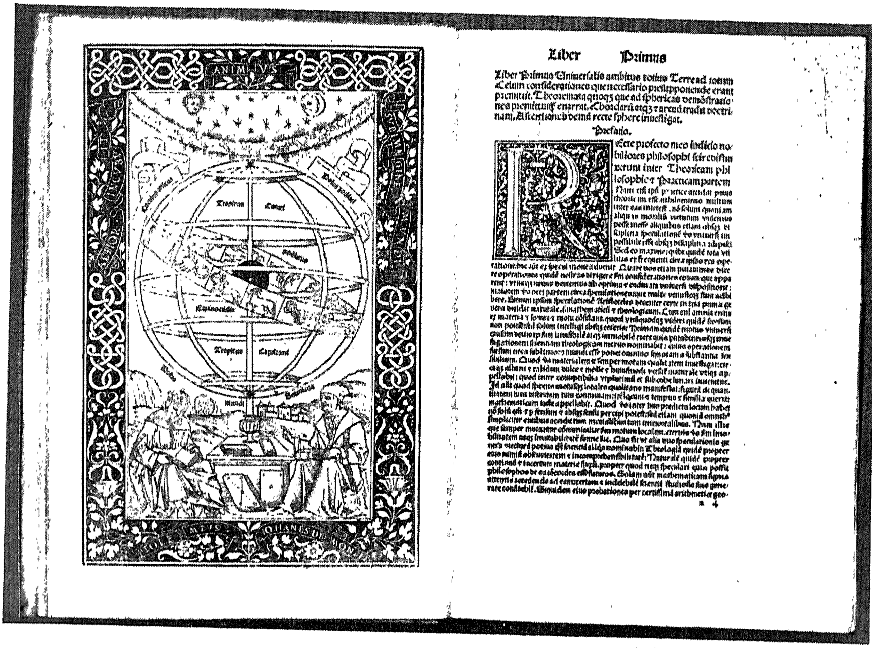
(*Metropolitan Museum of Art.*)

Fig. 22. Printing office, seventeenth century.

including the "Ephemerides" in which were the tables used by Columbus for finding latitude.

The Challenge to Authority. Growing intellectual, political, and religious ferment stimulated reactions in all fields of human activity. The Renaissance introduced a new spirit and renewed interest in thought and knowledge. Reformers became active in every field. The wide printing of the Bible and the new independence of thought encouraged the Protestant Reformation. The study of other Greek philosophers and the rebirth of individual thinking challenged the authority of Aristotle. The time was ripe for a fundamental criticism of traditional astronomy, and indeed of all sciences.

Interest in astronomy manifested itself especially in Germany where the spirit of independence was strong. The University of Vienna (founded in 1364) became a center of astronomical research. Johann Müller (1436–1476), known as Regiomontanus, studied at Vienna and in Rome. He accurately translated Ptolemy's *Almagest* as well as other scientific works. He moved to Nuremberg where he was financed by the citizens and enabled to build an observatory which remained in operation well into the seventeenth



(*Metropolitan Museum of Art.*)

Fig. 23. Pages from Regiomontanus' "In Almagestu Ptolomei" (1496).

century. One of his major accomplishments was the publication of a widely circulated book on planetary theory.

Navigation and Astronomy. The period of the great explorers, begun by the Portuguese expeditions sent out by Prince Henry in the fifteenth century, emphasized the dependence of navigation upon astronomical advances. Latitude (see Fig. 24) could be obtained as accurately as the crude instruments on shipboard would permit, for example, from the angle between the zenith and the north star. The determination of longitude (see Fig. 25), however, required a measurement of the position of the sun, moon, or a charted star, as well as the knowledge of the time of day at some reference meridian of longitude (often 0° longitude).[1] Few of the explorers of this period attempted to determine longitudes for lack of clocks that would keep time on rolling ships. In addition,

[1] Local time (p. 78) changes with longitude at the rate of 1 hr per 15°. Thus the longitude of a point can be obtained by comparing the time at that point with the time for 0° longitude, now at the Greenwich meridian. The time at the point can be derived from an astronomical observation (see p. 81) and the other from a clock set to give time corresponding to 0° longitude.

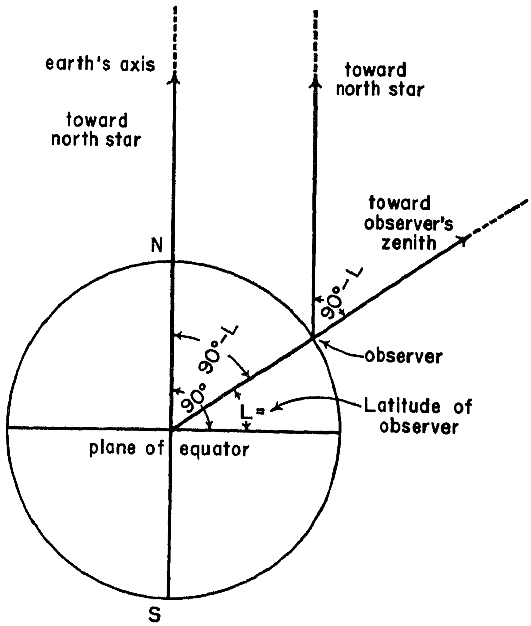


Fig. 24. Latitude L can be obtained from the angle between the polestar and the observer's zenith.

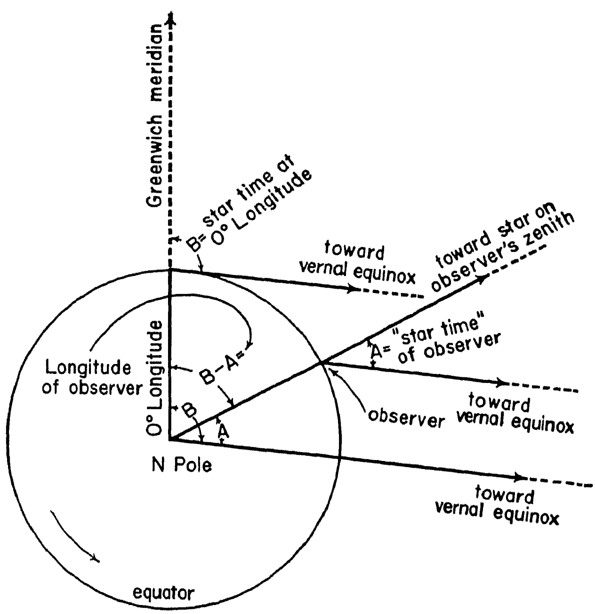
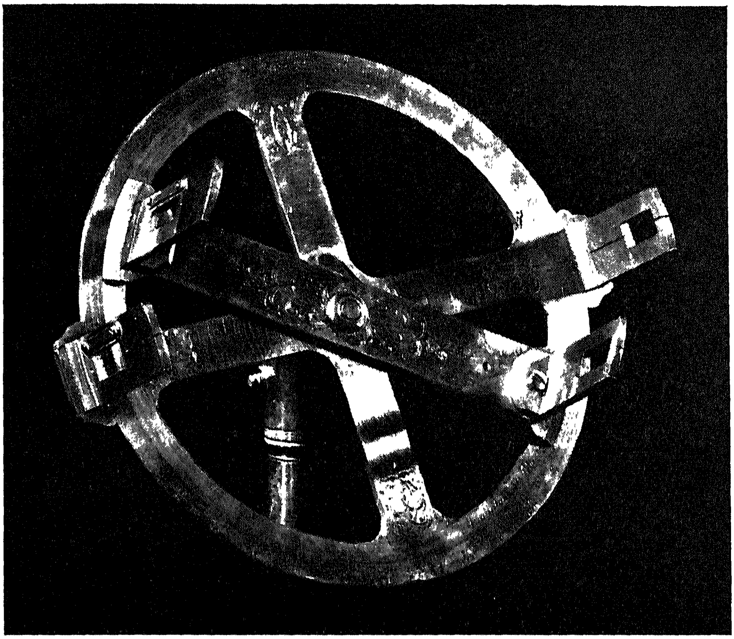


Fig. 25. Longitude can be obtained from Greenwich startime (B) and the observer's startime (A). The latter can be found from tables when a listed star is on the observer's zenith.

the preparation of adequate astronomical tables would have required not only a great series of accurate observations, but an accurate description of the motion of the solar system, with which to predict positions of the stars, moon, and sun.



(*American Museum of Natural History, New York.*)

Fig. 26.—Astrolabe such as was used by early navigators.

COPERNICUS AND THE HELIOCENTRIC SYSTEM

It was a propitious moment in history for the entrance of a man with the ingenuity and originality of Copernicus. When Columbus was discovering America, Nicolaus Copernicus (born 1473 in Poland) was a student at the University of Cracow, where he became deeply interested in mathematics and astronomy. After studying in Italy at Padua and Bologna, Copernicus lived for a number of years with his archbishop uncle in Germany, and there began to develop his revolutionary ideas about astronomy. Later, while holding a minor religious position at Frauenburg for some thirty years, he gradually worked out a mathematical foundation for his new concepts. In all this period he published nothing, possibly because he hesitated to precipitate an open controversy. Nevertheless, it ultimately became known that he held the novel

doctrine that the earth was in motion and the sun and stars at rest. This led to a great deal of criticism from many of his contemporaries. Martin Luther took occasion to say forcefully that Copernicus was a fool to hold such opinions, which were obviously contrary to the Bible.

Copernicus's *De revolutionibus* was finally published on the day of his death in 1543. It is certainly one of the most important books on astronomy, ranking with the *Almagest* and Newton's *Principia*. The central idea in the book probably marks the first real appreciation of relative motion: that many of the apparent motions of celestial bodies are not actual, but result from the motion of the earth carrying the observer along with it. Copernicus took the hazy speculations of Philolaus, Aristarchus, and others, developed the fundamental principles, and then showed not only that the heliocentric system gave a much simpler explanation of the observed motions of heavenly bodies, but that mathematically it was at least as accurate as any of the variety of forms of the traditional Ptolemaic system.

Copernicus showed that, from the viewpoint of an observer on the earth, the apparent daily rotation of the heavens from east to west about an axis through the poles could be explained equally well by a daily rotation of the ***earth*** from ***west*** to ***east*** about an axis through its poles. To meet the criticism that objects would be thrown from the surface of a rotating earth, Copernicus pointed out that such a rotation would be vastly more dangerous for the huge celestial sphere than for the comparatively small and solid earth. He also showed that the older view of an apparent annual motion of the sun around the earth could just as well be explained by an annual motion of the earth in a nearly circular path around the sun.

Copernicus then demonstrated that the apparent retrograde motion of a planet as observed from the earth could be explained by the combination of the annual motion of the earth around the sun and the motion of the planet around the sun. From the observed motions he correctly concluded that the order of the planets by distance from the sun was Mercury, Venus, Earth, Mars, Jupiter, and Saturn, and estimated their relative distances. He also computed that their times for revolution about the sun (***periods***) were in the same order, and ranged from 88 days for Mercury to about 30 years for Saturn. The earth thus became

merely one of the six (then known) planets circling the sun, and only the moon was left to rotate about the earth.

The Seasons According to Copernicus. Copernicus also argued that the motion of the earth around the sun accounted very well for the seasons. Figure 27 illustrates this point.

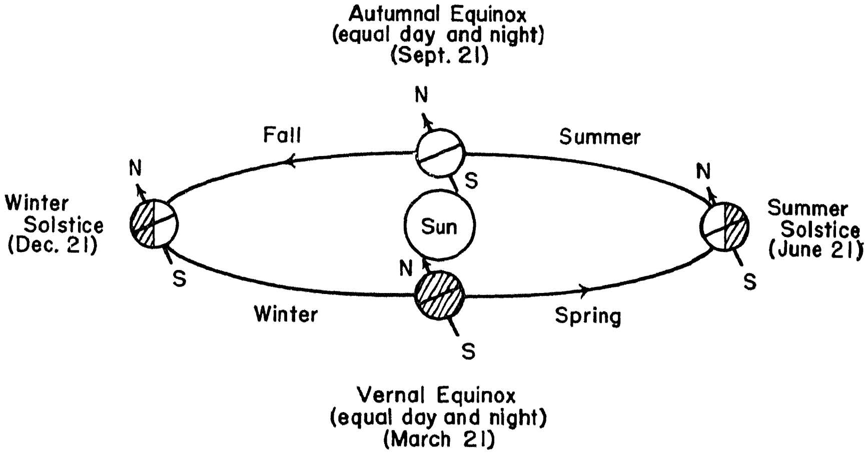


Fig. 27. Copernicus explained the seasons. Seasons occur because the earth's axis is not perpendicular to the plane of the earth's orbit. There is sunlight more than half the day in spring and summer—less in fall and winter.

Copernicus provided a strong argument for the overthrow of the Ptolemaic system. However, he did find it necessary to consider the sun as placed slightly off the center of the circle of the earth's orbit in order to obtain reasonable agreement with the poor observations then available. Not until some half a century later was the reason for this discrepancy to become clear.[1]

Considering the revolutionary nature of its contents, comparatively little public excitement was created by the publication of *De revolutionibus*. Perhaps this was because it was dedicated to the Pope, and because its nature made it quite unintelligible to all except mathematicians and astronomers. Although condemned by Luther, it was supported in some Protestant universities. Astronomers everywhere were soon familiar with Copernicus's work and on the whole accepted it.

The Prussian Tables, new and more accurate astronomical tables based on Copernicus's data, were published by Reinhold in 1551 and served to familiarize men with the Copernican theory.

[1] See Kepler's laws of planetary motion, p. 49.

Interest in astronomy was growing, and there were by that time many astronomy departments in the new universities. Measurements were still inaccurate; for example, errors in the accepted latitudes of important seaports ranged from one-half degree to several degrees. As discrepancies in the Prussian Tables were made apparent, it became clear to most astronomers that a long-continued program of accurate observation was necessary before any satisfactory conclusions about astronomical theories were possible. To meet this need, observational technique was improved considerably during the latter part of the sixteenth century. Furthermore, mathematical methods had been improved greatly, so that by the beginning of the seventeenth century three great devices had become available to save enormous labor in computation: the Arabic notation, decimals and fractions, and logarithms. The time was ripe for observational astronomy.

THE BEGINNINGS OF MODERN ASTRONOMY

Tycho Brahe, the Great Observer. Modern astronomy is greatly indebted to the observational genius of Tycho Brahe (1546–1601). The son of a Danish nobleman, Tycho studied astronomy with some interest at the Universities of Copenhagen, Leipzig, and Rostock, but his real enthusiasm for the subject was later stimulated by the sudden appearance of a new star (nova) in the constellation Cassiopeia. Frederick II of Denmark, who encouraged scientific work, granted the island of Hveen to Tycho and also arranged for sufficient funds to construct and maintain a castle and exceptionally well equipped observatory. The telescope had not yet been invented, but Tycho devised a number of excellent instruments, and by use of carefully graduated quadrants as large as 19 ft in radius he achieved a new order of accuracy. For 21 years Tycho and a corps of students and assistants maintained a program of continuous and highly accurate observations of the sun, the moon, the planets, and some 777 fixed stars. An enormous mass of data was thus accumulated. Disagreements with the government, however, caused Tycho to move in 1599 to Prague, where he died in 1601 before he had completed cataloging his life's work.

Tycho Brahe owes much of his fame to the brilliant use made of his observations by his assistant and successor at Prague, Kepler, who came to him only 14 months before his death. Tycho's own belief was a curious mixture of the Copernican and Ptolemaic

(*From a diorama at the Buhl Planetarium.*)

Fig. 28. Tycho Brahe's observatory at Hveen.

systems. He supposed the sun to be the center of the planetary system, but he insisted upon the right to consider the earth as the center of the cosmos, in the absence of experimental evidence to the contrary. Actually, this evidence eluded observers until more than a century and a quarter after Tycho's death.

Kepler Discovers the Laws of Planetary Motion. The association of Johann Kepler (1571–1630) with Tycho Brahe was exceedingly

fortunate, for he was just the man needed to make use of Tycho's accurate observations. Himself a poor observer because of his weak eyesight and bad health, Kepler had an excellent background in mathematics. At the request of the Emperor Rudolph he completed the Rudolphine Tables, new astronomical tables based on

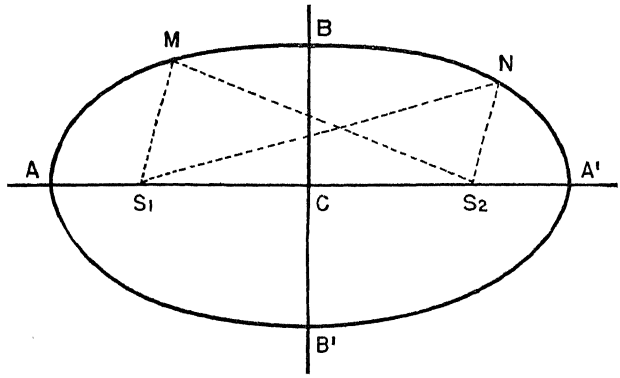


Fig. 29. The ellipse. A planet moves along an ellipse with the sun at one of the foci, S_1 or S_2. The sum of the distances from the two foci (S_1 and S_2) to the planet remains constant (that is, $MS_1 + MS_2 = NS_1 + NS_2 = AS_1 + AS_2 = AA'$). The shape of an ellipse depends on its eccentricity: $e = CS_1/CA = CS_2/CA'$. If S_1 and S_2 are brought together, e becomes zero and the ellipse becomes a circle. If S_1 and S_2 are moved to A and A′, e becomes unity and the ellipse is narrowed into a segment of a straight line. Actually, the planetary paths are almost circular, the greatest certain eccentricity, 0.206, being that of Mercury.

Tycho's data. These served as standards of observation for astronomers and navigators for many years.

Animated by a Pythagorean faith in the harmoniousness of the universe, Kepler searched more than 20 years for simple relations between the motions of the planets. Much of his effort was spent trying to determine the actual path of the planet Mars from its apparent path which necessarily included the effects of motion of the observer on the earth. He made many careful computations, trying combinations of circles, ovals, and various figures, but they did not agree with Tycho's observations, and so could not be reconciled with the actual path even though the differences were in some cases no more than eight minutes of arc.

Finally, in 1609, Kepler assumed an elliptical path, and found that if the sun were supposed to be at one focus of the ellipse this path for Mars fitted Tycho's data beautifully! At last the solution to the old problem was discovered. Kepler quickly tried elliptical paths for the other planets, and there also they worked within the

limits of error. After considerable further study of the planets' orbits, Kepler announced his three celebrated conclusions, known as Kepler's laws of planetary motion:

1. *The orbit of each planet is an ellipse with the sun at one of the foci.*

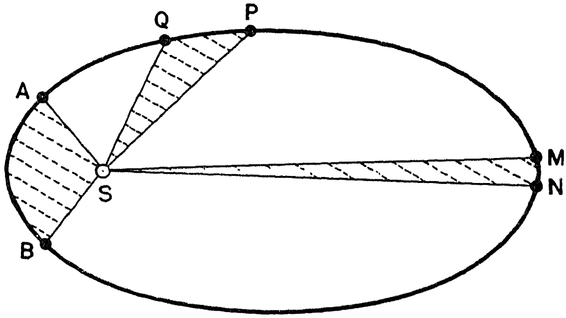


Fig. 30. Keplers' law of areas. (The eccentricity has been exaggerated.)

2. A line from the center of the sun to the center of the planet ***sweeps over equal areas of the ellipse in equal times.*** Thus, as shown in Fig. 30, each planet moves in its orbit so that, if S is the sun, the line AS sweeps over the area ASB when the planet moves from A to B. However, on the other side of the orbit, a planet will have to move only from N to M in the same time in order that the area NSM = area ASB. Similarly in the region from P to Q it travels at an intermediate speed. Thus the planet travels faster in its orbit the nearer it is to the sun.

3. Kepler's third law describes the relationship between the periods of revolution of the planets in their orbits and their distances from the sun—***the squares of the periods of revolution of the planets about the sun are proportional to the cubes of the mean distances from the sun.*** Thus if T_A and T_B are the periods of revolution of two planets, and R_A and R_B their mean distances from the sun, then

$$\frac{(T_A)^2}{(T_B)^2} = \frac{(R_A)^3}{(R_B)^3}$$

or this may be written in the form

$$\frac{(T_A)^2}{(R_A)^3} = \frac{(T_B)^2}{(R_B)^3} = K$$

K is a constant for all planets.

For example, suppose that we wish to find the period of Mars, and already know the period and distance for the earth and the distance for Mars. Then if A refers to Mars, and B to the earth, and using the mean radius of the earth's orbit as a unit of distance which we shall call one ***astronomical unit,*** we have:

$$T_B = 1 \text{ year}$$
$$R_B = 1 \text{ astronomical unit}$$
$$R_A = 1.52 \text{ astronomical units}$$

Then

$$(T_A)^2 = \frac{(T_B)^2}{(R_B)^3} \times (R_A)^3 = \frac{(1 \text{ year})^2}{(1 \text{ ast. unit})^3} \times (1.52 \text{ ast. units})^3$$
$$= 3.51 \text{ years}^2$$
$$T_A = \sqrt{3.51 \text{ years}^2} = 1.87 \text{ years}$$

The actual value is 1.88 years. Note that as we carry along the various units, the astronomical units cancel, leaving the answer in years.

It should be remarked that Kepler's laws apply accurately only to a planet that is sufficiently far from the other planets. When comparatively close together, planets have motions that deviate by small but measurable amounts from the descriptions given by these laws. These deviations are discussed further on page 60.

EXPERIMENTAL VERIFICATION OF KEPLER'S THIRD LAW*

Planet	Distance from sun (R), AU	Orbital period (T), years	R^3	T^2
Mercury	0.387	0.241	0.0580	0.0581
Venus	0.723	0.616	0.378	0.379
Earth	1.000	1.000	1.000	1.000
Mars	1.52	1.88	3.51	3.53
Jupiter	5.20	11.86	141	141
Saturn	9.54	29.46	868	868
Uranus	19.19	84.0	7,070	7,060

* Neither Neptune nor Pluto has had one complete period since its discovery.
NOTE: $T^2 = R^3$ as closely as can be expected (so T^2/R^3 = constant = 1).

After his many years of patient effort, Kepler was of course enthusiastic about his success in providing the long-sought accurate description of planetary motion. Even though existing reports of his work were ordered burned and their publication forbidden, the triumphs of his method were soon well known. Although prompted

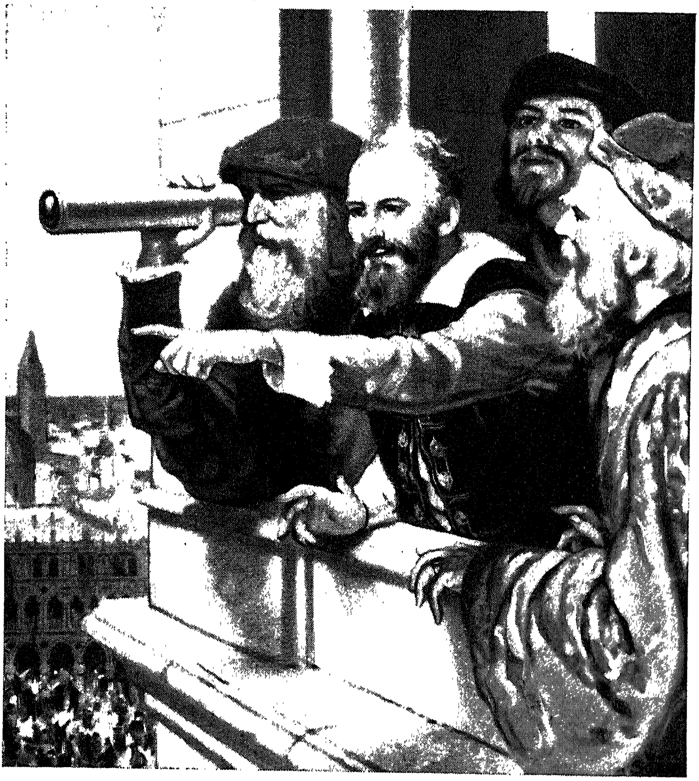
by an almost mystic faith, Kepler's work marks the beginning of the modern treatment of scientific problems, and is an excellent example of the interrelation of experimental observation and theory. Within the limits of observational error, phenomena in nature were shown to be describable by simple mathematical expressions.

Galileo and Experimental Science. Early experimental science owes much to the inspiration of Galileo Galilei (1564–1642). He was one of the first to make extensive use of the experimental method. In 1581 Galileo commenced the study of medicine at the University of Pisa, but he soon found that his real interest was in experimental science and mathematics. His unwillingness to accept dogmatic teachings and his tendency to argue earned him the dislike of some professors, and the nickname "The Wrangler."

Galileo's contributions to mechanics began early. While still a student, the motion of the large hanging chandelier in the cathedral attracted his attention. No stop watch was then available, but he used his pulse as one, and discovered that whether the lamp made large swings or small swings, the time for one vibration (the period) remained the same. Later he investigated the pendulum more completely, and shortly before his death he designed the first pendulum clock.

In 1589 Galileo was appointed to a professorship of mathematics at the University of Pisa, with a munificent stipend equivalent to $65 a year. While at this post, Galileo developed the basis for a real understanding of mechanics, and his concepts of velocity and acceleration are those now in use. At Pisa he also conducted his dramatic experiments on falling bodies. Aristotle's dictum that the rate of fall of a body depends on its weight was generally accepted, but we know of no one before Galileo who gave it a direct experimental test. Many accounts have it that after numerous experiments had shown him the falsity of this idea, a public demonstration was arranged at which Galileo dropped two very unequal weights from the Leaning Tower. Even though the crowds saw the balls start, fall, and strike the ground together, they still preferred to believe Aristotle rather than the experimental proof which they themselves had witnessed. In the end, Galileo's original ideas and "heretical" utterances led to so much opposition among his colleagues that he was forced to resign his post at Pisa.

In 1592 Galileo became a professor at Padua, a strong and progressive center of learning, and there he lectured in a more congenial atmosphere on such diverse subjects as mechanics, astronomy, geometry, heat, and fortifications.

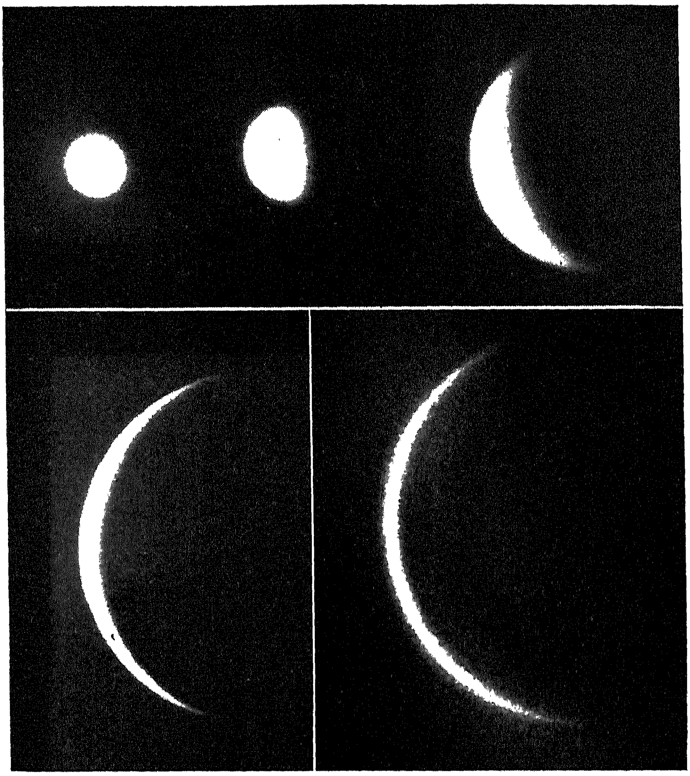


(*Bausch and Lomb.*)

Fig. 31. Galileo demonstrated his first telescope from the tower of Saint Mark's Church at Venice.

At Padua, in 1609, Galileo heard the rumor of the invention of the telescope, usually attributed to the Flemish spectacle maker, Hans Lippershey. Although lacking details of this invention, Galileo immediately began to experiment with combinations of concave and convex lenses. With his knowledge of optics, Galileo was soon able to construct a far better instrument than Lippershey's original, with a magnification of more than 30 times. Galileo went to Venice to show the telescope to the Signori, who were much impressed by seeing ships at sea two hours before they entered the harbor. Telescopes were soon widely used in many countries and became indispensable to navigators.

Appreciating the great possibilities of the telescope in astronomy, Galileo quickly used it to investigate the heavens. He turned his telescope toward the moon, and man saw for the first time its mountains and craters. He turned it toward the Milky



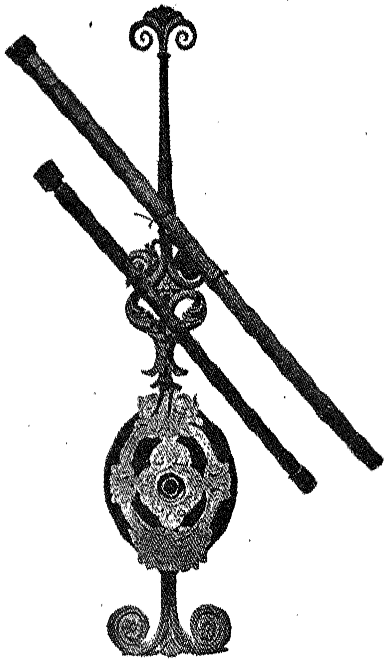
(*E. C. Slipher, Lowell Observatory.*)

Fig. 32. Venus—Photographs showing various phases and relative apparent sizes. When seen as a small disk, Venus is on the opposite side of the sun from the earth, when a thin crescent it is on the same side—hence the apparent difference in size.

Way, and legends overturned, for this was actually a swarm of faint stars. The rings of Saturn were observed. He saw the spots on the sun, and from their motion concluded that the sun rotated. On Jan. 7, 1610, Galileo discovered four satellites of the planet Jupiter, and observed them revolving about Jupiter. Then the earth was not the center about which everything revolved! Here was direct proof that a system of bodies revolving about a central body other than the earth is possible in nature. Turning to Venus, he found that it exhibited a regular progression of phases like the

moon, in complete contradiction to Aristotle and Ptolemy. It was obvious that Venus revolved about the sun, and was illuminated by light reflected from the sun.

With all this confirming evidence, Galileo became a firm believer in the heliocentric theory. His difficulties, however, were multiplying. Some men refused to believe what they saw in his telescope, and some even refused to look. Galileo's small patience with those who did not agree with him did not help matters. In 1600 Bruno was burned at the stake for heretical beliefs including the heliocentric theory, and antagonism toward Galileo grew rapidly.



(*Louis Bell.*)

Fig. 33. Telescopes of Galileo.

In 1610 Galileo left the Venetian Republic to accept an invitation to Florence, where he came under the dominion of the Pope. By 1615 opposition to the new thought had succeeded in having all books on the Copernican theory condemned. In spite of all this, Galileo published his *Dialogues on the Ptolemaic and Copernican Systems*. This was written in the form of exceptionally clever conversations between Sagredo, a keen wit, his old Venetian friend, Salviati (who expressed Galileo's own point of view), and Simplicio—a rather dull fellow—who upheld Aristotle and the Ptolemaic system. Galileo's brilliant arguments, his aggressive nature, and his attacks on orthodox scholars had brought him into so much conflict with certain elements in the powerful church, even before his brazen publication of the *Dialogues*, that the appearance of the book was enough to have him summoned before the Inquisition in Rome. During his trial the aging Galileo underwent the keenest humiliation, and at its conclusion he was forced to recant and abjure all statements implying that the earth moved around the sun. Nevertheless, his spirit was not broken, for it is said that, when he was finally released

from the Inquisition chambers, he departed muttering to himself, "and still it moves!"

During the semi-imprisonment which lasted the rest of his life, Galileo completed a great treatise on dynamics entitled *Discourse on Two New Sciences*. In this work, published outside Italy in 1638, Galileo set forth the results of his long experimentation and reasoning on mechanics and bodies in motion. The concepts of inertia, momentum, velocity, and acceleration were dealt with so admirably that Newton's first two laws of motion were anticipated.[1]

Most important of all for science was Galileo's use of the experimental method, and his demonstration of the dangerous nature of conclusions based solely on authority, opinion, and prejudice. Others had advocated experiment, but Galileo was the first to use it with thorough effectiveness. To him no phenomenon was inaccessible to experiment. Even astronomy was to become more than simple observational science. The age of modern experimental science had begun.

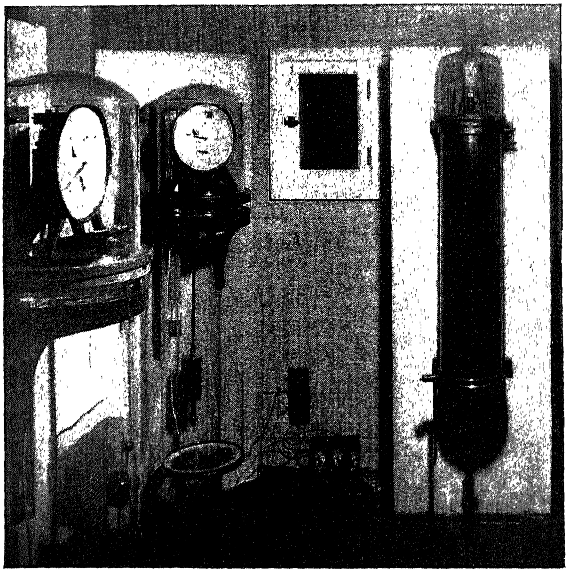
Spread of the Experimental Method. The successes of Copernicus, Kepler, and Galileo stimulated activity in the various fields of science and mathematics, but we can consider only briefly the steps taken. It is difficult to separate sharply the developments in physics and mathematics from those in astronomy. In Belgium, Stevinus (1548–1620), a contemporary of Galileo, contributed much to mechanics. In France, Descartes (1596–1650) deduced a number of axioms from the work of Galileo and Stevinus, and wrote *The System of the World*. This book was more philosophical than experimental, but his ideas inspired many experiments.

An increasing number of excellent men were becoming interested in science as the training in the universities was improving. In Holland and later in France, Christian Huygens (1629–1695) distinguished himself in mathematics, physics, and astronomy. Galileo had discovered the isochronism of the pendulum, but Huygens first successfully applied the pendulum to regulate an escapement mechanism and thus control it for timekeeping. Huygens bridged the gap between the mechanics of Galileo and Stevinus and that of Newton and LaGrange. His studies of centrifugal force, of mass, and of impulse and impact in collision problems became very important to astronomy. Huygens also made great

[1] See Newton's laws of motion, p. 58.

contributions to optics, especially in the design of telescopes and through his work on the wave theory of light.

Timepieces in Astronomy. In addition to the pendulum clock, Huygens invented the watch operated by a spiral spring, intended



(*Courtesy of The Sky.*)

Fig. 34. Heart of the time-keeping system of this country. Clock vault of the United States Naval Observatory.

especially for use at sea. It was not, however, until 1735 when a means of compensating the effects of temperature change was found that timepieces were accurate enough to make practical the measurement of longitude on ships. Continued refinements in construction have actually reached such a point that clocks of the Shortt type maintain the correct time to within 0.02 sec for a month. Accurate clocks to supplement astronomical determinations of time are exceedingly important to astronomical observatories. Today standard time signals by radio make accurate time measurements available everywhere on earth, so clocks may be checked constantly by this means.

Newton and the Mechanistic Universe. In the same year that Galileo died, Isaac Newton (1642–1727) was born in England—a man to whom nearly every field of science owes a profound debt. Even before taking his B.A. at Cambridge in 1665, Newton discovered

the binomial theorem. Soon afterward he developed the methods of infinitesimal calculus almost simultaneously with Leibnitz (1646–1716), the famous German mathematician. Thus evolved one of our most powerful mathematical tools. Eventually Newton revolu-

(*Courtesy of The Sky.*)

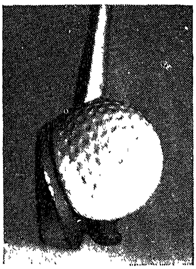
Fig. 35. Sir Isaac Newton.

tionized the treatment in nearly all branches of mathematics and created many new subjects as well. Newton became a Fellow of Trinity College, Cambridge, in 1667 and was appointed Lucasian Professor of Mathematics in 1669. In the quiet atmosphere of that university he was free to carry on his brilliant work for many years.

Newton's monumental work was set forth most completely in his *Philosophiae naturalis principia mathematica* (1687), probably the most important single scientific book ever written. With the work of Galileo, Stevinus, Huygens, and others as a basis, he succeeded in formulating a complete, consistent system of mechanics starting from simple fundamental principles. Newtonian mechanics gave such an accurate description of phenomena in nature that the mechanistic conception of the universe soon came to permeate all science and philosophy. Although we recognize today that his description of motion is not strictly complete, the corrections

involved in the more accurate representation given by the theory of relativity are negligibly small except in special cases.

Newton's Laws of Motion. Newton's famous three laws of motion are the starting point for all our dynamics:



(*Edgerton, Germhausen and Grier.*)

Fig. 36. "To every action there is an equal and opposite reaction." The force exerted by the ball on the club is equal and opposite to the force exerted by the club on the ball. Photograph taken with high-speed motion-picture camera.

1. Every body continues in a state of rest, or of uniform motion along a straight line, unless compelled to change that state by impressed forces.[1] (That is, it is in the nature of matter itself to continue to move as it is doing, and the only way to make its motion different is to apply a force.)

2. The rate of change of momentum (Newton called it "quantity of motion") of a body is proportional to the force producing the change and takes place in the direction in which that force acts. (The momentum of a body is its mass × velocity and it possesses the direction of the velocity. The above gives a quantitative relationship as soon as the units are clearly defined. This suggests that forces, like most other entities, are to be measured by means of the effects which they produce.)

3. To every action, there is an equal and opposite reaction. (This may be phrased in terms of a specific case. Body A cannot push on body B unless body B pushes on body A with a push equal in magnitude and opposite in direction. "Force," we understand, could be used in place of the word "push.")

In order to make a perfectly general description of the way that a body falls toward the center of the earth, Newton assumed that there must be a pair of attractive forces, one acting on the body and an equal but opposite one acting on the earth—forces of gravity. The force acting on the body we call the ***weight*** of the body.

In extending this concept to the problem of the motion of the moon around the earth and later to that of the planets around the sun, Newton reasoned that, in order for the motion to be maintained, there must be equal and mutually attractive forces between the heavier central body and the body moving around it. He concluded that such forces must be proportional to the product of the

[1] See p. 148 on force.

masses of two bodies (that is, the quantity of matter in the two bodies) and inversely proportional to the square of the distance between them.

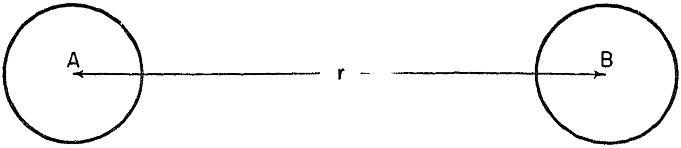


Fig. 37.

Let us see what this means. Suppose that there are two bodies, A and B, at some distance apart, as in Fig. 37. Let us use the following symbols:

$$
\begin{aligned}
M_A &= \text{mass of body } A \\
M_B &= \text{mass of body } B \\
r &= \text{distance between } A \text{ and } B
\end{aligned}
$$

Then for either of the two gravitational forces of attraction which A and B exert on one another, we have

$$f \propto \frac{M_A M_B}{r^2}$$

($\propto$ means "proportional to"). If there were no other forces acting on them, the two bodies would approach each other. If the mass of A alone were doubled, the gravitational forces between A and B would become twice as large. If the distance r between A and B were doubled, the forces would become one-fourth as great. We may drop the proportionality sign if we write this expression

$$f = G\frac{M_A M_B}{r^2}$$

where the constant G depends upon the units in which the masses, force, and distance are measured. The researches of Cavendish and others have shown that if we express the masses in ***kilograms,*** the distance in ***meters*** (see page 146), and the force in ***newtons*** (see page 148), then

$$G = 6.664 \times 10^{-15}\ \frac{\text{newton-meter}^{2*}}{\text{kilogram}^2}$$

* 6.664×10^{-15} is a short notation for a decimal number in which 6.664 is 15 places to the right of the decimal point—*i.e.*, 0.000000000000006664.

Thus we can say that every particle of matter in the universe attracts every other particle with a force that is inversely proportional to the square of the distance of separation.

Newton concluded that the moon departs from motion along

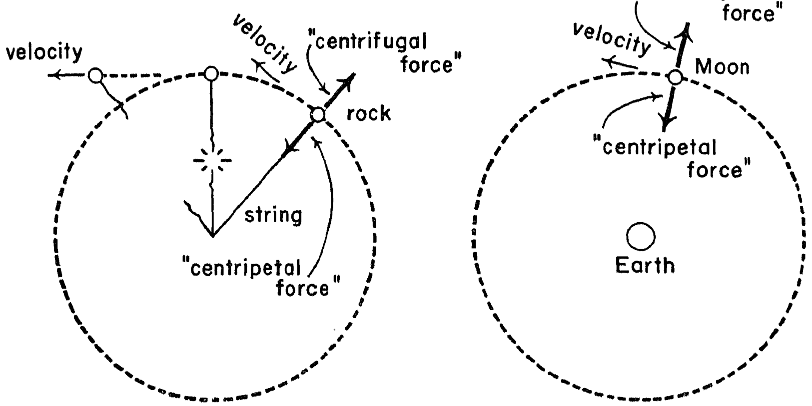


Fig. 38. The gravitational force exerted by the earth on the moon serves as the centripetal force which holds the moon in its orbit. This is similar to the case of a stone swung in a circle by means of a string, where the pull of the string on the stone is the centripetal force.

a straight line because the gravitational force of attraction exerted by the earth upon the moon is directed toward the earth's center. This is called a ***centripetal force.*** It can be considered that this force is exactly balanced by an outward force (***centrifugal force***) on the moon, such that the moon is in equilibrium under the two forces, and is free to revolve indefinitely in its orbit (Fig. 38). Newton discovered that if the inverse square law of attraction were true, Kepler's laws of equal areas and of the relationship between period and distance automatically followed. He believed, however, that computation of the moon's motion would require knowledge of the distribution of the earth's mass, so he lost interest in the matter. Some years later Newton proved that for purposes of calculation the mass of the earth could be considered as concentrated at the earth's center. Then he found that his theory checked almost exactly with actual measurements!

The calculations were extended with fairly good agreement to the case of the planetary orbits about the sun. Newton realized that each planet could not be considered as revolving around the sun completely independently of other planets. Small irregularities or "perturbations" in the motion of each planet were produced

by the attractive forces of neighboring planets, and these forces varied with the relative positions of the planets. Such perturbations were of course much more pronounced when the planets were nearest each other, that is, at *conjunction*. Later research has

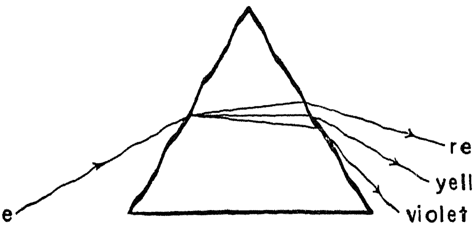


Fig. 39. Formation of a spectrum by a prism.

shown that, as these effects are taken into account, the agreement between Newtonian theory and observation becomes practically perfect.

Newton's law of universal gravitation gave an excellent description of the motion of the solar system in simple mathematical terms. At last celestial mechanics was on a firm basis and the Copernican theory established beyond question! It should be realized, however, that such a description of "how" the solar system operates does not in the end answer, or even attempt to answer, "why" such laws as that of universal gravitation exist.

Newton and Optics. Newton added much to our knowledge of optics. He favored the corpuscular theory of light, which postulates that light is composed of a stream of tiny particles, rather than Huygens' wave theory. Newton demonstrated that ordinary *white* light is composed of different colors which may be separated into a *spectrum* when passed through a glass prism, that is, each color is bent or *refracted* differently. This discovery made spectroscopy possible. Spectroscopic investigation was to yield much important information in astronomy and physics.

The separation of white light into its component wave lengths by a prism is called dispersion (see Fig. 39). *Chromatic aberration,* or color distortion, due to this type of separation of the colors, was very disturbing in *refractor,* or lens-type, telescopes. To minimize this disturbance, Newton devised the *reflecting* telescope, in which the convex lens is replaced by a concave mirror.

Newton gratefully recognized that his achievements were made possible by the work of those who had gone before. "If I have seen farther than Descartes, it is by standing on the shoulders of giants."

Leibnitz, his rival, said of him: "Taking mathematics from the beginning of the world until Newton's time, what he has done is much the better half." And according to LaGrange, Sir Isaac Newton "was the greatest genius that ever existed, and the most fortunate, for we cannot find more than once a system of the world to establish."

Organization of Scientific Societies. All branches of science advanced at an ever-growing rate in the period following Newton, accelerated especially by the founding of a number of scientific societies which made provision for publication of scientific discoveries. The ***Royal Society of London,*** founded in 1662, has continued to be one of the most important scientific organizations. Its publication is now called the *Proceedings of the Royal Society.* Newton was one of the first Fellows of the Royal Society, and was its president during the last 24 years of his life (1703–1727). The ***French Royal Academy*** was founded by Louis XIV in 1666, but did not begin publishing its transactions regularly until about 1700. The ***Berlin Academy*** began its meetings in 1700. In America, the ***American Philosophical Society,*** proposed by Benjamin Franklin, was organized in 1769.

Societies specifically for astronomy were not organized until the nineteenth century. The first of these, the ***Royal Astronomical Society,*** known also as the ***Astronomical Society of London,*** was founded in 1820. German and French astronomical organizations followed in 1863 and 1887, respectively. In this country, the ***Astronomical Society of the Pacific*** (1889) was the first to be organized, and in 1899 the ***Astronomical and Astrophysical Society of America*** was formed.

Further Astronomical Developments. Observational astronomy made rapid strides during the eighteenth century. Newly designed telescope mountings with carefully divided circles greatly increased the accuracy of astronomical observations.

In 1676 a young Dane, Olaus Römer (1644–1710), reported to the French Academy a series of careful observations on Jupiter's moons which proved that the velocity of light is finite.

Römer measured the velocity of light by the time required for light reflected from Jupiter's satellites (one is indicated in Fig. 40) to traverse a distance equal to the diameter of the earth's orbit.

He determined the time between successive eclipses of one of Jupiter's brighter satellites by observations when the earth was at E_1 (near conjunction). Then, 6 months later, when the earth was at E_2, the eclipses were seen to occur about 1,320 sec later than

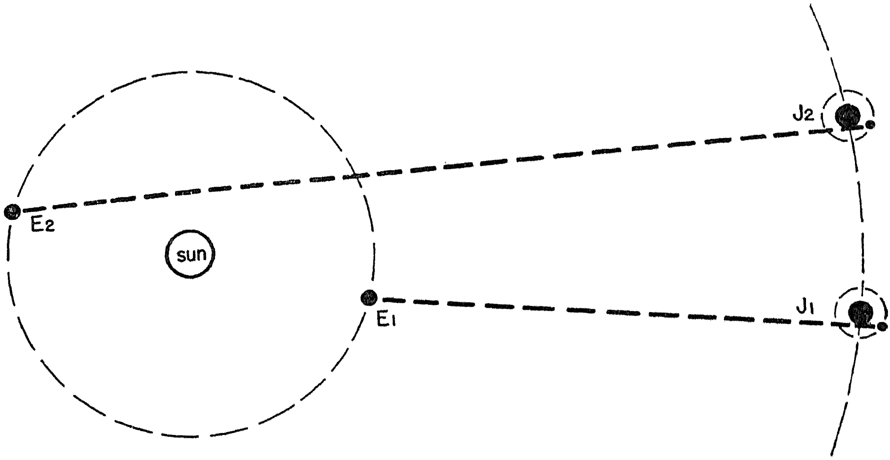


Fig. 40. Römer measured the velocity of light.

was to be expected from the schedule previously established. This discrepancy he correctly concluded was due to the time taken for the light to traverse the earth's orbit. If we apply Römer's method, using the modern value of 996 sec for this time discrepancy, and take the diameter of the earth's orbit as 186,000,000 miles, the velocity of light is 186,000,000/996 or about 186,000 miles per second. This is very close to the value which has been determined by more recent methods.

It is interesting to note that, many years before, Galileo had attempted to measure the velocity of light by determining the time required for a light signal from a suddenly uncovered lantern on one hilltop to be seen by a man stationed on another hill a mile away and a return light signal to be seen by the original observer. Although the elapsed time was so small that no definite results could be obtained, Galileo believed that the velocity of light was finite.

Among other observers active in Newton's time was John Flamsteed (1646–1719), first Astronomer Royal at the newly founded Observatory at Greenwich (from which our longitude is now measured). He made a long series of systematic and highly accurate observations of the positions of the moon, planets, and

some 3,000 stars. Whereas Tycho's observations were accurate to about 1 minute of arc, Flamsteed's were within 10 seconds of arc. Halley (1656–1742), Flamsteed's successor at the Greenwich Observatory and a friend and helper of Newton, continued this

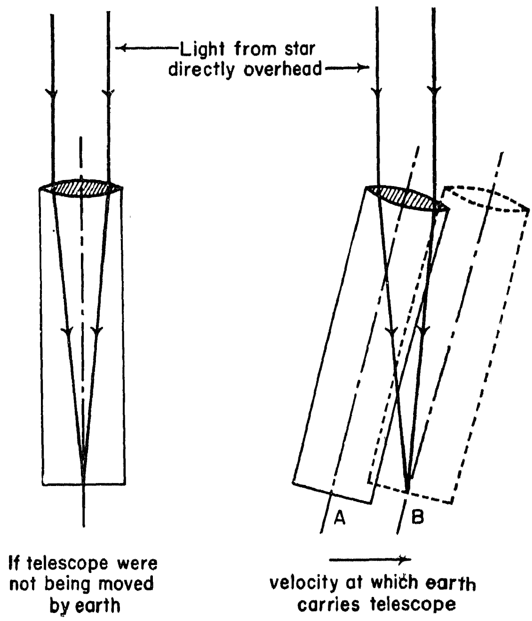


Fig. 41. Aberration of light. The telescope is carried sideward by the earth, so it moves from A to B (exaggerated greatly) while light travels the length of the telescope. Thus, for light to remain centered in the telescope, the instrument must be tilted slightly.

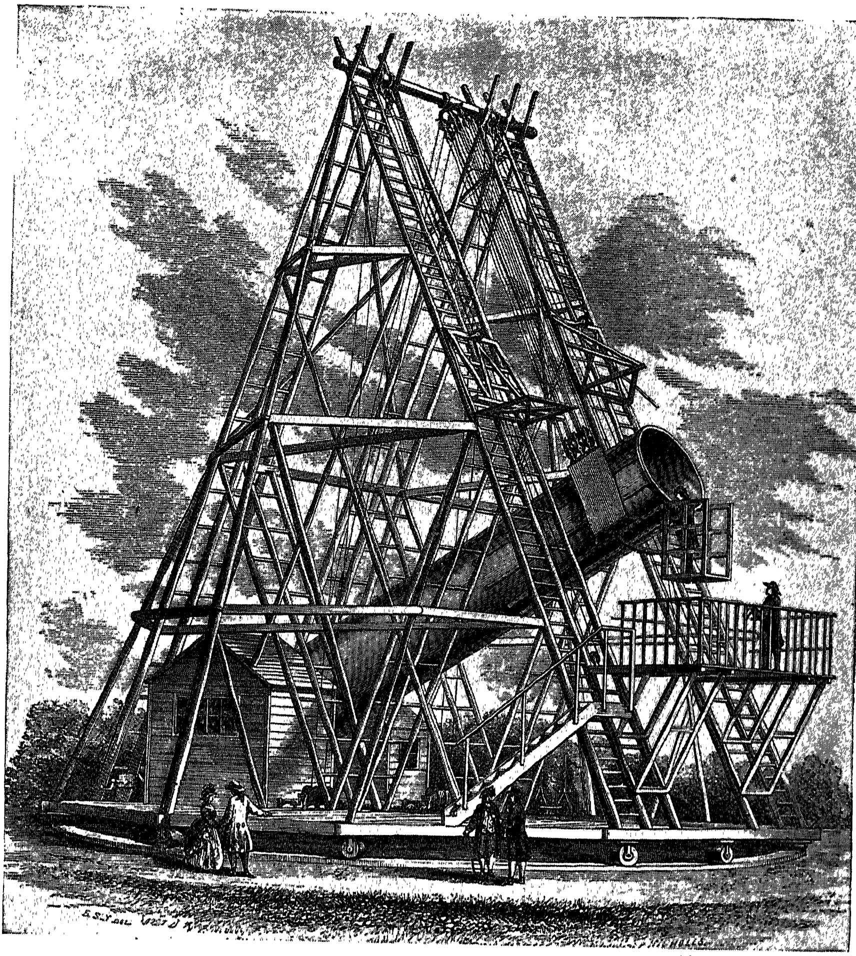
work and made numerous observations on the paths of comets. James Bradley (1693–1762), third Astronomer Royal, further improved the accuracy of observation so that errors were usually less than 4 seconds of arc. He attempted to solve the problem that has intrigued astronomers ever since Copernicus—to observe the apparent displacement of the "fixed" stars which should be caused by the change of the earth's position in its orbit. Instead, in 1727, he discovered another phenomenon, ***aberration of light,*** an apparent displacement of stars due to the combined effect of the velocity of the earth in its orbit and the velocity of the light from the star (Fig. 41). Although by different means than intended, this gave the first direct experimental evidence that the earth moves with respect to the stars—184 years after the publication of the Copernican theory! Bradley concluded that the appar-

ent change of star positions caused by the travel of the earth in its orbit is probably not greater than one second of arc, which meant that the "fixed" stars were very much farther away than had been realized.

Meanwhile developments in mathematics and the theory of mechanics kept pace with observation, so that gravitational investigations were carried much beyond Newton's laborious calculations. As has been mentioned, the motion of a given planet around the sun cannot be treated as a simple problem of the motion of two bodies because of the perturbing effects of the other planets. Since no rigorous solution to the general problem of the motion of three (or more) bodies has ever been found, methods of approximation had to be developed.

Most prominent among the brilliant men who combined mathematics with astronomy and physics and who generalized and extended Newton's work were Leonhard Euler (1707–1783), Alexis Clairaut (1713–1765), Jean d'Alembert (1717–1783), Joseph LaGrange (1736–1813), and Pierre Laplace (1749–1827). Laplace's *Celestial Mechanics* marked a great achievement in the description of motion in the solar system, but he is popularly remembered more because of his ***nebular hypothesis*** regarding the origin of the solar system. He suggested that the solar system was once a twirling shapeless mass of hot rarefied material, that is, "nebulous" material. As the mass cooled and shrank, its outer portion separated into irregular rings which finally congealed to form the planets, while the remaining matter became the sun. This idea has lost favor to the "tidal" hypothesis that a star passing near the sun pulled from it the parts which formed the planets.

Herschel. The work of Frederick William Herschel (1738–1822) did much to open a new phase of astronomy, in which the methods of physics were combined with astronomy in what we call today ***astrophysics***. Although primarily a musician, Herschel was deeply interested in astronomy and spent all his leisure time in constructing a number of excellent reflector telescopes of the Newtonian type. With the aid of his sister Caroline, who recorded his observations and computed for him, Herschel began an intensive program of study. Herschel discovered in 1781 what he thought at first was a comet, but found to be a new planet, which he called *Uranus*. This won him such scientific acclaim that George III appointed him his private astronomer with an annual grant of



(*Courtesy of The Sky.*)

Fig. 42. Sir William Herschel's 40-ft. reflector at Slough, England.

£200. He built a succession of larger telescopes and in 1789 constructed one 40 ft. long with a 48-in. mirror.

Herschel was one of the first to study the distribution of stars in space. He discovered that the band-shaped cluster of stars comprising the Milky Way, or the galaxy, is really a huge disk-shaped family of stars. Our sun, located about three-fifths of the way from the center to the edge of the galaxy, is one of its secondary stars. Herschel's comparatively large telescopes made it possible for him to study distant "island universes" or ***galactic nebulae.*** Among his other discoveries were the existence of ***double stars,*** close pairs of

stars which revolve about each other and which therefore show that gravitation is indeed universal. He also studied ***variable stars,*** which vary in intensity. Sir William Herschel made the first measurements that showed the motion of the solar system through space and was perhaps the first to introduce modern astrophysical methods for investigating the nature of radiation from celestial bodies. In 1800 he found that if a thermometer were placed in the spectrum of the sun's light, formed by a prism, it showed the presence of radiation beyond the limit of visible red light—***infrared radiation.*** After his death, his sister Caroline Herschel and later his son Sir John Herschel (1792–1871) carried on his work in brilliant fashion. The Herschels left with us the conception of a universe far vaster than anything previously imagined.

FOR STUDY AND READING

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SUMMARY

Systematic astronomical observations were made by ancient priests studying the deities of the sky. Objective thought about natural phenomena began with Thales (about 600 B.C.). Succeeding Greek philosophers of nature included Leucippus, Democritus, Pythagoras, Aristarchus, and the great Aristotle (384–322 B.C.), whose ideas of a geocentric universe dominated astronomical thought for 20 centuries. Archimedes in Alexandria was the first to make full use of experiment in science. The better known astronomers of Greek Alexandria were Eratosthenes, Hipparchus,

and Ptolemy, author of the *Almagest* and elaborator of Aristotle's geocentric theory.

Science in western Europe all but died under Roman domination, and remained neglected through the middle ages. Meanwhile scientific discoveries of the Greeks were preserved and slightly amplified by the Arabs, and were brought back to Europe after A.D. 1000 as commerce developed between the growing city states and the East. It was not until the church began to decline politically that independent thought commenced to challenge the prevailing philosophical dogma. The development of printing (1456) revitalized all fields of learning. Astronomy was encouraged for navigation purposes.

Copernicus (1473–1543) seriously questioned the geocentric theory when he published in *De revolutionibus* strong evidence for a heliocentric theory of the solar system. Tycho Brahe (1546–1601) obtained a new order of accuracy in extended astronomical observations, and Kepler used these observations as a basis to develop his three "laws" describing planetary motion. Galileo (1564–1642) was a champion of experimental science, whose contributions to astronomy included studies in dynamics and the astronomical telescope. Galileo also studied the pendulum, and Huygens used it to make the first dependable clock—essential for astronomical work. The achromatic lens was another invention of Huygens.

Newton (1642–1727), one of the greatest scientists, gave to astronomy his three laws of motion and a description of gravitational force, new mathematical methods, improvements of the refractor telescope, and the first reflector telescope.

During Newton's time the organization of scientific societies and creation of the Greenwich Observatory spurred astronomy. Römer of Denmark, and Flamsteed, Halley, and Bradley, the first three English Astronomers Royal, made important astronomical observations. Mathematical astronomy advanced in the hands of Euler, Clairaut, d'Alembert, LaGrange, and Laplace. William Herschel (1738–1822) originated the science of astrophysics and discovered the planet Uranus as well as the existence of double stars and of galaxies.

QUESTIONS

1. What part did religion and the early priests and astrologers play in beginning experimental observation? How far did early civilizations such as that of the Babylonians progress?

2. In what way did the development of Greek science represent a much higher level than that of earlier civilizations?
3. How has the long line of Greek thinkers from Thales and Pythagoras to Aristotle greatly influenced the thought of succeeding ages?
4. What led to general acceptance of the geocentric theory of the universe? What were the chief features of this theory?
5. Why might Archimedes be considered one of the first great scientists?
6. What factors helped arrest the growth of science during the 14 centuries from the Greek school to Copernicus? Are such factors operating today?
7. What were the main scientific contributions of the Arabs?
8. What relation was there between the end of the domination of physical concepts by Aristotle's philosophy and the development of the experimental method in the work of Copernicus, Galileo, Tycho Brahe, and others?
9. What are the basic differences between Copernicus' model of the solar system and Ptolemy's modification of the Aristotelean model?
10. Aristotle's scheme of planetary orbits, illustrated in Fig. 11, was designed to explain observations such as those in Fig. 10. Why then do these two figures look so different?
11. Upon what experimental work were Kepler's three laws of planetary motion founded?
12. What complication is indicated by small deviations from Kepler's laws in their simple form?
13. How does the work of Tycho Brahe, Kepler, and Newton illustrate the effectiveness of a combination of theory and experiment?
14. Taking Neptune's distance from the sun as 30 times that of the earth, how many years are required for Neptune to trace its orbit once?
15. How many complete revolutions about the sun has Neptune made since its discovery?
16. What are some of Galileo's contributions to astronomy?
17. Of what astronomical importance are Newton's laws of motion?
18. What is the magnitude of the gravitational force exerted by the moon on the earth? The earth on the moon? The sun on the earth?
19. In what way does the work in the fields of physics, chemistry, and mathematics by Newton, Huygens, Laplace, and others show the interdependence of all fields of science?

CHAPTER III

A MODERN SCIENCE—ASTRONOMY TODAY

DEVELOPMENT OF ASTRONOMICAL INSTRUMENTS

We have seen how the progress of astronomy has depended largely on the development of experimental methods of observation. Consequently, let us consider more carefully the tools used by the astronomer.

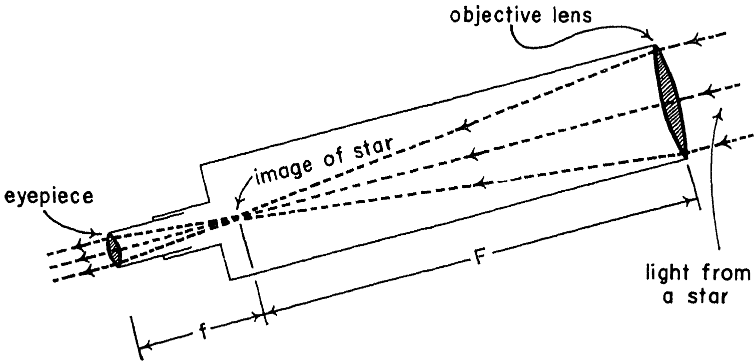
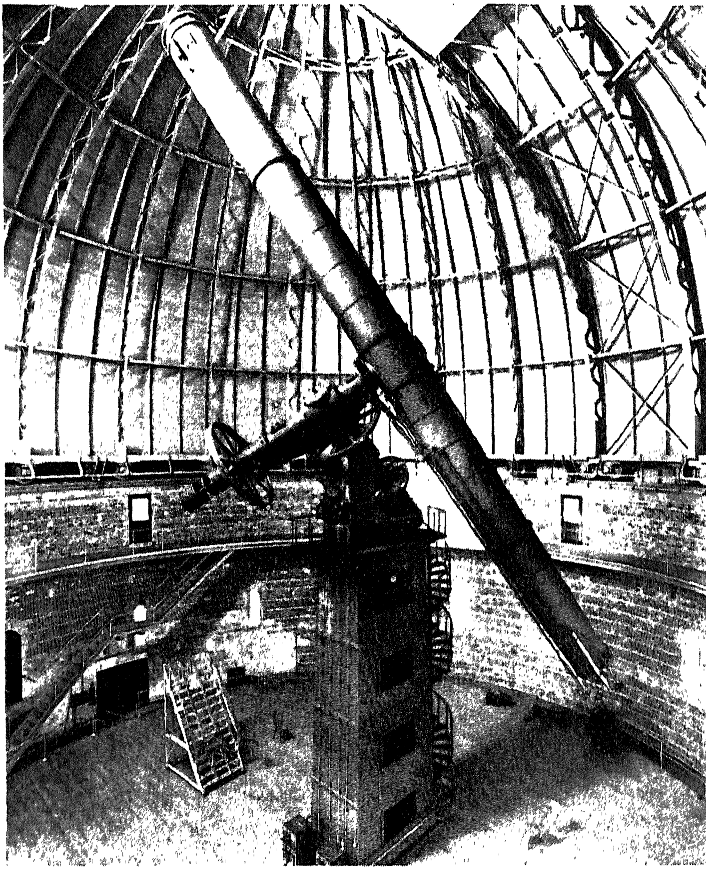


Fig. 43. Refractor telescope.

Telescopes. Of all astronomical instruments, the telescope has undoubtedly been the most important. Much was learned about the approximate courses of sun, moon, stars, and planets before its invention, but very little detailed knowledge even of the solar system, and certainly little of the vast regions of space beyond it, would have been forthcoming without the telescope. The telescope performs two major functions: (1) it magnifies an object, so that we may see it in detail, and (2) it makes visible objects too faint to be seen by the naked eye. Astronomical telescopes are of two general types: *refractor* and *reflector.*

Refractor-type Telescopes. The present-day refractor-type astronomical telescope, first proposed by Kepler, consists essentially of two convex lenses (Fig. 43) and is a modification of

Galileo's form which had a convex lens and a concave lens. The "rays" of light from a distant star or planet are parallel, and after passing through the large convex objective lens are brought to a focus at a distance F from the lens, F being known as the ***focal***



(*Yerkes Observatory.*)

Fig. 44. Forty-inch refractor of Yerkes Observatory.

length. A ***real image*** of the star is thus formed at F. Light from neighboring stars may be focused to form images at different points in the plane which is at the distance F from the lens. These images are then viewed through the eyepiece, which may be a short-focus convex lens of focal length f, used as a magnifying lens. Actually, eyepieces are usually made of a combination of two small lenses, a modification first introduced by Huygens to reduce chromatic aberration (page 61).

The *magnification* of such a telescope is the ratio of the focal length of the objective lens to the focal length of the eyepiece, or

$$\text{Magnification} = \frac{F}{f}$$

In practice the magnification of a telescope is changed by using eyepieces with various focal lengths. The shorter the focal length of the eyepiece, the greater the magnification.

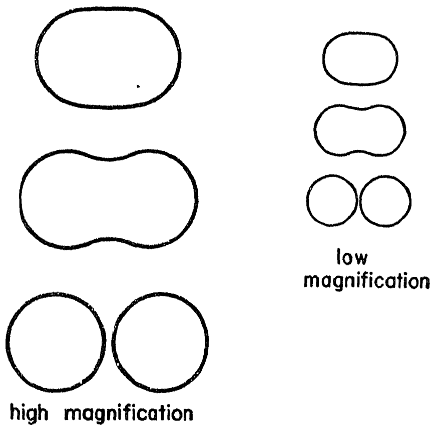
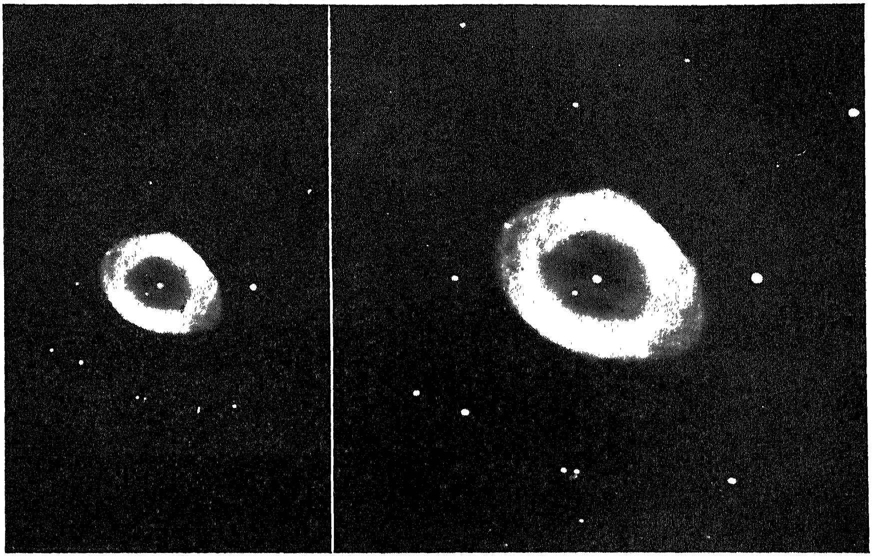


Fig. 45. Increasing magnification alone does not increase resolving power. Overlapping disks representing star images are no easier to distinguish in the enlarged figure than in the smaller one. Stars are so distant that their images would be immeasurably small rather than apparent disks if it were not for diffraction of light (Chap. XVIII), disturbances in the atmosphere, and effects within the telescope and the photographic plate. The size of the apparent disk increases with increased exposure (Fig. 54).

The *light-gathering power* of such a telescope is its ability to make objects visible that are too faint to be seen by the unaided eye. It depends on the *area* of the objective lens, because the area determines the amount of the light energy from the object that can be intercepted by the lens and brought to a focus. The maximum effective aperture (diameter) of the pupil of the eye is about one-fourth inch. The diameter of the largest objective lens yet made, that of the Yerkes telescope of the University of Chicago, is 40 in. The ratio of the area of the Yerkes lens to that of the eye is, therefore, $(40/\frac{1}{4})^2$, or more than 25,000. Thus, with the aid of the Yerkes telescope, objects may be seen which are 25,000 times fainter than those visible to the eye alone. (Strictly, this would be true only under perfect atmospheric conditions.) Even fainter images, however, could be observed on a photographic plate.

Another exceedingly important property of the telescope and all other optical instruments is the *resolving power*. This is the ability to distinguish between two objects that appear to be close together, and is determined fundamentally by the diameter of the objective lens and the color of the light. It has no relation to magnification. The resolving power increases in proportion to the



(*Mount Wilson Observatory.*)

Fig. 46. Region about the ring nebula in Lyra photographed with the 100-in. and 60-in. reflectors at Mount Wilson. If it were not for effects such as atmospheric disturbances, etc., the ability to distinguish between two adjacent star images should increase with the diameter of the objective. The perfection of individual telescopes differs considerably.

diameter of the objective lens. This is one of the most important reasons for using large objectives.

Serious difficulties inherent in refractor telescopes were apparent in Newton's time. The chromatic aberration caused by separation of white light into its component colors becomes increasingly serious with higher magnifications and larger lens apertures. The achromatic double-lens eyepiece of Huygens improved one part of the system, but the real difficulty comes in the objective lens. A great advance was made with the discovery that chromatic aberration could be reduced by making the lens in two or more sections, each composed of glass of different refractive properties. Fine camera lenses often have four or even six lens sections, which also serve to reduce distortions other than chromatic aberration. ***Achromatic doublets*** are reasonably successful for a small lens. However, they merely reduce the aberration, since a two-section lens corrects accurately for only two colors or wave lengths. For a lens as great as 40 in. in diameter, enormous labor is required to grind and polish even a single surface to the necessary precision, and for a doublet with four surfaces the difficulties become almost

prohibitive. In addition, it is difficult to secure large pieces of good optical glass.

Reflector-type Telescopes. The reflector telescope, as we have seen, was introduced by Newton to reduce the difficulties charac-

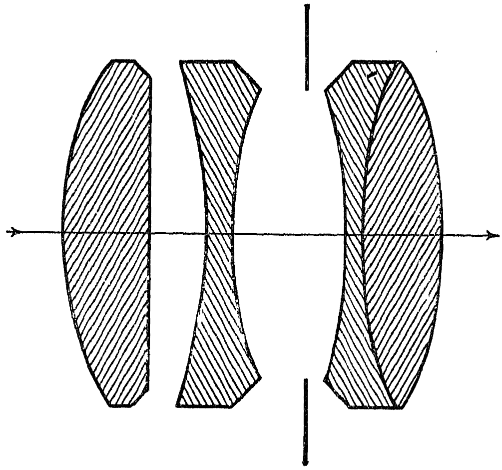


Fig. 47. Kodak Ektar camera lens. Precision photographic lenses are made in several sections to minimize distortion.

teristic of the refractor type. As can be seen in Fig. 48, the principle is essentially the same as that of the refractor—a real image of the distant object is formed by the parabolic concave mirror at a total distance from the mirror equal to the focal length F. This may

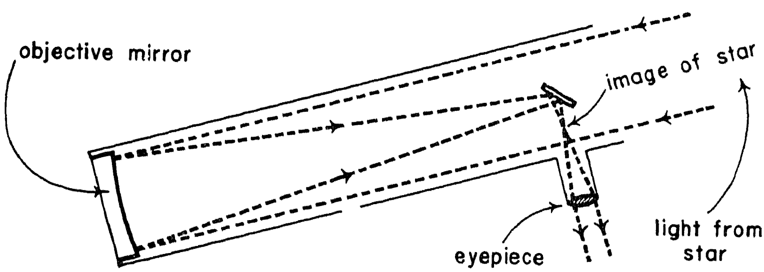
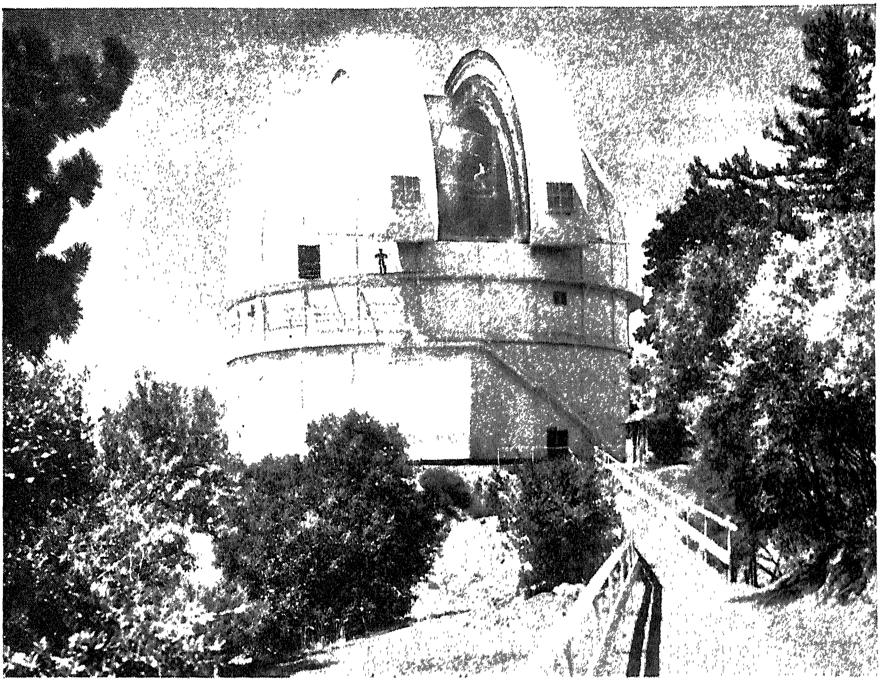


Fig. 48. Reflector telescope.

involve a reflection toward the side of the main tube of the telescope by a small secondary mirror. This real image is then viewed through the eyepiece. The magnification is given by F/f, just as in the refractor.

The objective mirror is front-silvered or, in the newer telescopes, aluminized. Hence the light is reflected without passing



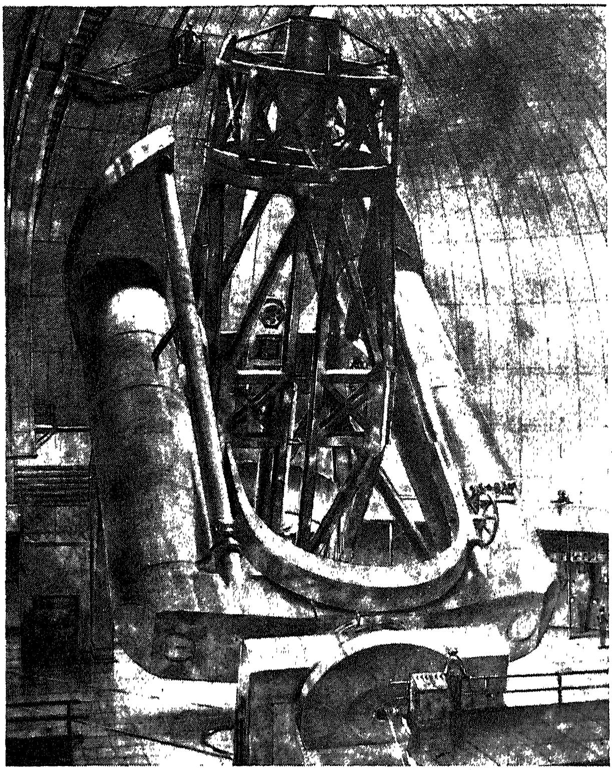
(Mount Wilson Observatory.)

Fig. 49. Dome housing the 100-in. telescope at Mount Wilson.

through any glass and suffers no chromatic aberration due to different refraction of the various colors. The new method of depositing a thin layer of aluminum for a reflecting surface gives appreciably better results than silver, especially for photographic purposes. Any type of glass or other material having the proper mechanical properties may be used for the mirror. The fact that only one surface needs to be accurately ground and polished, instead of at least four surfaces as in a corrected refractor lens system, greatly simplifies production and makes feasible much larger objectives. A lens must be supported at the edges only, but because a mirror may be mounted from behind on a reinforced steel system, large mirrors may be supported successfully without sagging.

Since the time of Herschel's 48-in. reflector, emphasis has been placed upon the size and quality of telescope mirrors. With each increase in light-gathering power, the size of the universe that man could explore was correspondingly enlarged as the progressively fainter light from ever more distant objects was made visible. A number of large reflectors are now, or soon will be, in use in North

America. Among them are the 72-in. reflector now in operation at the Dominion Astrophysical Observatory at Victoria and the 74-in. telescope at the Dunlap Observatory in Toronto. An 82-in. reflector was recently completed at the McDonald Observatory in



(*Astrophysical Observatory, California Institute of Technology, Pasadena.*)

Fig. 50. The Mount Palomar telescope.

Texas, and an 85-in. telescope is planned for the University of Michigan. The 100-in. telescope of the Mount Wilson Observatory has made it theoretically possible to see objects 160,000 times fainter than can be seen with the eye alone. A new 200-in. reflector (nearly 17 ft. across) is now being put into operation at Mount Palomar; the pyrex glass mirror weighs over 20 tons, and its casting, grinding, and polishing have taken several years. With its elaborate mounting, the telescope will weigh nearly 2,000 tons. This tremendous project is a striking example of scientific knowledge and engineering skill.

Atmospheric disturbances probably set an upper limit to optimum mirror size, but theoretically such a mirror as the one at Mount Palomar will have a light-gathering power of about 640,000 times that of the unaided eye. Since light intensity decreases inversely as the square of the distance from the source, this increase by a factor of four in light-gathering power over that of the 100-in. telescope should increase by a factor of two the distance at which the same object could be seen. Since refinements have also been made in the secondary mirror and eyepiece system, it is expected that under exceptionally good atmospheric conditions the new telescope will actually be able to "see" about three times as far as the 100-in. telescope. This indicates an increase in the volume of the visible universe of nearly 30 times. Of what this may mean we shall learn more in the next two sections.

Star Positions. It was apparent even in ancient times that some standard way of recording star positions was necessary, so that measurements made at various times by different observers could be compared. As accurate astronomical instruments and clocks were developed, there evolved the present system of locating stars. This is called the ***equator system.*** To sight a star, it is necessary to know only its direction and not its distance. Consequently, it is usual to think of the stars (and other astronomical bodies) as placed on a huge ***imaginary*** sphere with the earth at its center—the ***celestial sphere*** (Fig. 51). For reference purposes there are celestial north and south poles, equator, hour circles, and parallels of declination on this heavenly sphere, which correspond exactly to the earth's poles, equator, meridians of longitude, and parallels of latitude.

Just as two quantities, latitude and longitude, describe the position of a point on the earth's surface, the similar quantities ***declination*** and ***right ascension*** are used in the equator system to describe the position of a star on the celestial sphere.

The ***declination*** of a star is simply the angle measured north (+) or south (−) from the celestial equator to the star. The declination of an observer's ***zenith,*** the point directly overhead on the celestial sphere, is of course just his latitude.

A star's ***right ascension*** is the angle measured eastward from a standard celestial hour circle.[1] Because the right ascension of an

[1] This hour circle passes through the ***vernal equinox,*** the position where the sun's apparent path (the ***ecliptic***) runs northward across the celestial equator.

observer's zenith changes with time of day, it is necessary to correct a star's right ascension for time in order to obtain the angle between the star's hour circle and the hour circle through the observer's zenith, known simply as the *meridian*. This angle is called the ***hour angle*** of the star. Thus, for convenience in making

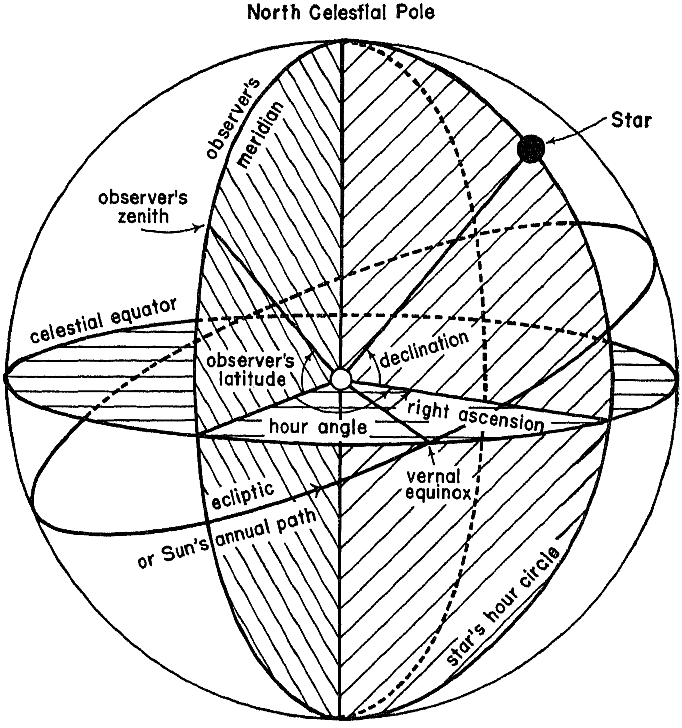


Fig. 51. The celestial sphere. The negligibly small earth is at the center.

this time correction, right ascension is specified in hours, minutes, and seconds instead of ordinary angular units. Twenty-four hours is then equivalent to 360 deg.

The Equatorial Mounting. The telescopes which we have discussed are usually supported on equatorial mountings. This type of mounting was especially developed for use with the equator system of specifying star positions. The main or ***polar axis,*** along AA in Fig. 52, is set parallel to the earth's axis, that is, it points toward the celestial north and south poles. The other axis, BB (the *declination axis*), is at right angles to it. By means of synchronous motors the telescope may be rotated westward about the polar

axis at a rate just equal to the rate of the earth's rotation about its axis, in order to compensate accurately for this eastward rotation of the earth. Thus the image of a star may be held in position in the field of view or on a photographic plate, to make possible continuous observation over long periods.

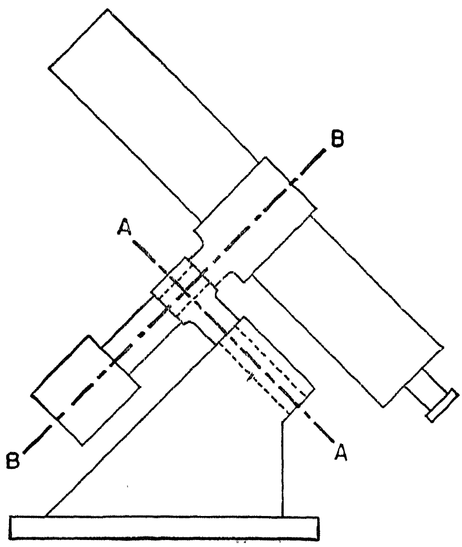
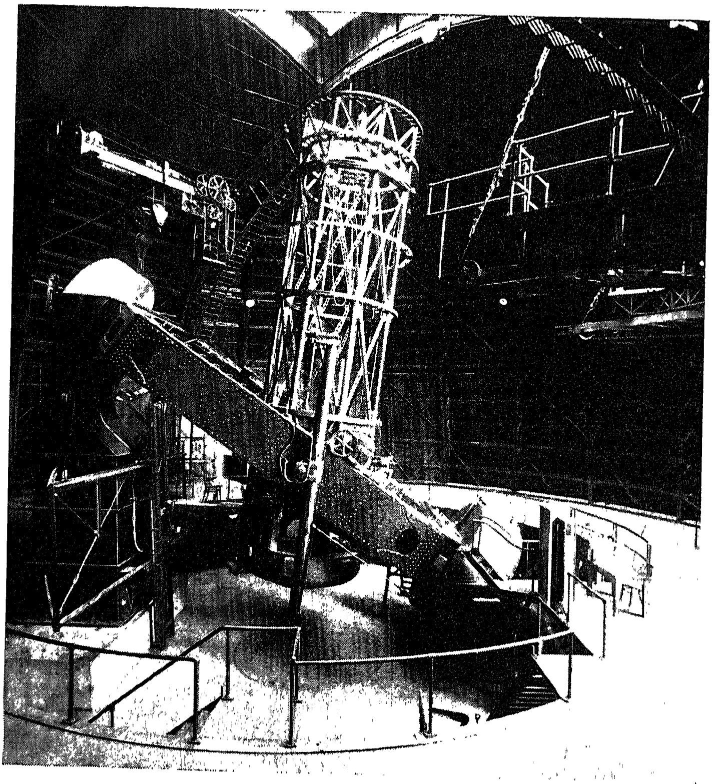


Fig. 52. Equatorial mounting.

As has been indicated, the equatorial mounting is convenient for use with the equator system of recording star positions. The hour angle of a star, obtained from the right ascension and time, is the amount the telescope is rotated about its polar axis when swung from the meridian to the star's hour circle. The star's declination is the angular rotation of the telescope about the declination axis when swung from the celestial equator to the star's parallel of declination. These two settings point the telescope toward the star under consideration.

Photography with Telescopes. The development of photography by Louis Daguerre (1789–1851) and its application to astronomical observation by William Bond of Harvard (1789–1859) and notably by L. M. Rutherfurd of Columbia (1816–1892) greatly increased the usefulness of the telescope. Permanent records of whole sections of the sky could then be made from time to time, and precise comparative measurements on the plates could be undertaken at any time later. Rutherfurd's long series of plates, made in the 1860s,

give us today a very valuable and accurate comparison with the past. Since 1865, virtually all quantitative studies have been made by the photographic method. In general, this method reduces the subjective errors that are inevitable in personal observation.

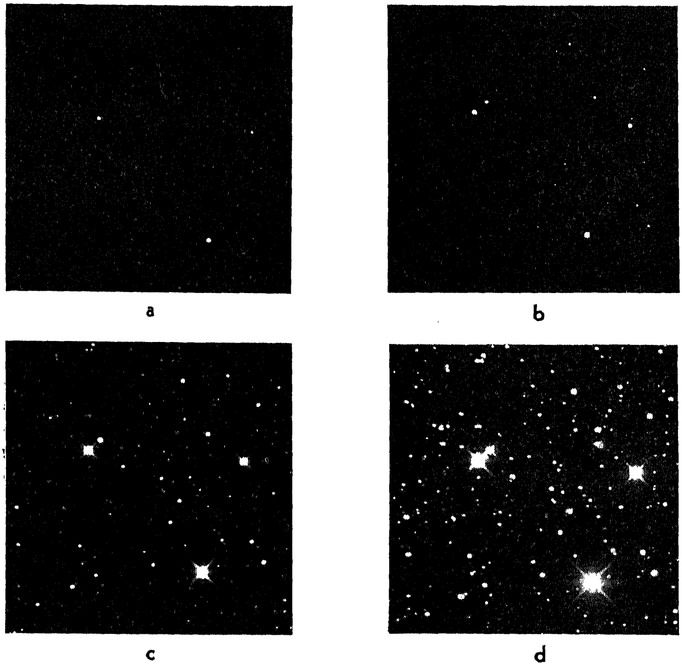


(*Mount Wilson Observatory.*)
Fig. 53. Mount Wilson 100-in. reflector.

Furthermore, long exposures build up visible images of exceedingly faint stars.

To make these records, a photographic plate is placed at the focus of the objective lens in a refractor, or of the concave mirror in a reflector, so that the telescope acts as a giant camera. Since photographic plates are usually most sensitive in the blue-violet region (whereas the eye is most sensitive in the yellow-green), either photographic refractor objectives are chromatically corrected for the blue-violet, or an additional lens section is added to the visual objective to provide this correction. Reflectors are of course perfectly achromatic under all conditions.

Time and Its Measurement. Time is one of the most important fundamental quantities, especially to the astronomer and physicist. The time of the earth's rotation on its axis, because it is very constant, has come to be used as the standard to which all time measurements

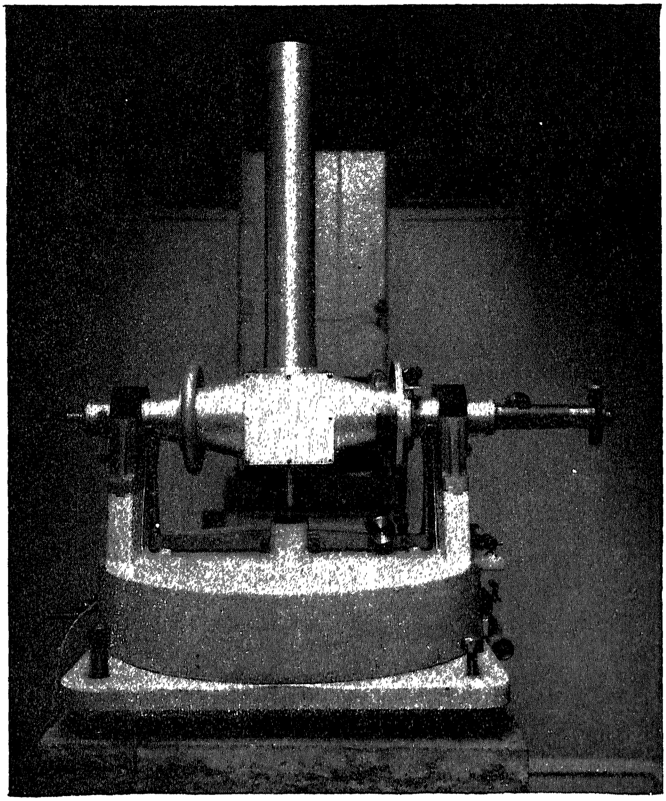


(Mount Wilson Observatory.)

Fig. 54. Increasing exposure time makes "visible" progressively fainter star images: (a) stars to twelfth magnitude; (b) stars to fifteenth magnitude; (c) stars to eighteenth magnitude; (d) stars to twentieth magnitude.

are referred. In astronomical work the unit of time most used is the ***sidereal day:*** the time required for the earth to make one complete rotation with respect to the stars. The ***transit*** is the instrument used to determine sidereal time from stellar observation. This is essentially a telescope mounted on an axis so that when it is rotated it always points toward the meridian (the observer's north-south hour circle). The time between successive appearances of a given star on the reference lines (cross hairs) in a transit telescope is very accurately 24 sidereal hours. Clocks or other secondary time standards may readily be checked to within 0.01 sec by such an instrument. Sidereal time designation ranges from 0 to 24 hr. The sidereal noon of an observer, or his 0 hour, occurs when the vernal equinox crosses his meridian.

In daily life, however, time referred to the sun, or ***solar time,*** is much more satisfactory than sidereal time or star time. The motion of the earth in its orbit causes the sidereal day to advance about four minutes each day with respect to sun time. For example,



(*Courtesy of The Sky.*)

Fig. 55. Transit at the Cook Observatory.

sidereal noon occurs at the same time as solar noon on Mar. 21, and it occurs at solar midnight on Sept. 21.

The time in civil use is based on ***mean solar time.*** Because of the varying velocity of the earth in its slightly elliptical orbit and because of the inclination of the plane of the earth's equator to the plane of its orbit (23.5 deg), the time between successive crossings of the meridian by the sun varies. It is sometimes slightly more, sometimes slightly less than 24 ordinary hours. In order to make days of uniform length, the average of these periods is taken to be 24 hr, and thus we actually use ***mean solar time.***

Strictly speaking, a given value of mean solar time applies only to one particular longitude. For convenience, local time belts have been established throughout the world. In each of these time belts one value of solar time is agreed upon as ***standard time.*** In

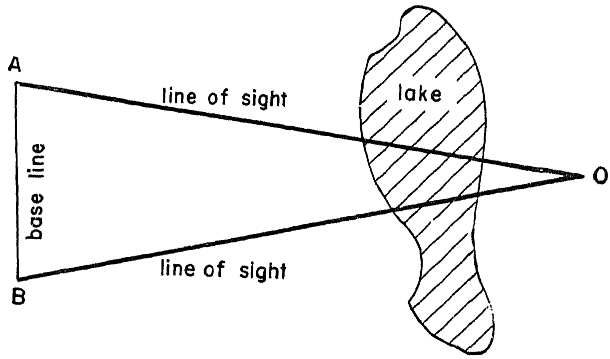


Fig. 56. Distance to inaccessible object by triangulation.

our own country, we have Eastern, Central, Mountain, and Pacific Standard time belts, the time in each differing by one hour from that in a neighboring belt.

Measuring the Distances to Stars and Planets. In order to measure the distances to celestial objects, the astronomer uses methods similar to those which the surveyor uses to determine distances to inaccessible objects. In Fig. 56, suppose that O is an inaccessible object and we wish to know the distance AO. If we lay down a base line AB, the length of which is accurately known, and then measure the two angles of the triangle at A and B, we may compute by trigonometric methods the distance AO. The error will be small if the base line AB is a reasonable fraction of the distance AO and if AB and the angles are accurately measured.

In measuring astronomical distances the chief difficulty is to get a sufficiently long base line so that the angles at A and B will be measurably different from 90 deg. For the near-by planets, a chord connecting two points on the earth, such as the 8,000-mile diameter of the earth itself, is a long enough base line—a set of measurements by two observatories at known distances apart on the earth gives fairly satisfactory results (Fig. 57).

The distances to the stars, however, are so great that a much longer base line is needed. Bradley made what was probably the first reasonably accurate attempt to measure stellar distance. He

used the diameter of the earth's orbit (186,000,000 miles) as base line, by comparing measurements on a star made six months apart (Fig. 58). Although he discovered the aberration effects mentioned previously (p. 64), which amounted to as much as 20.5

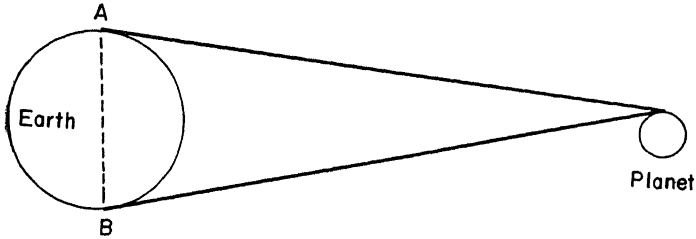


Fig. 57. Distance to planet by triangulation.

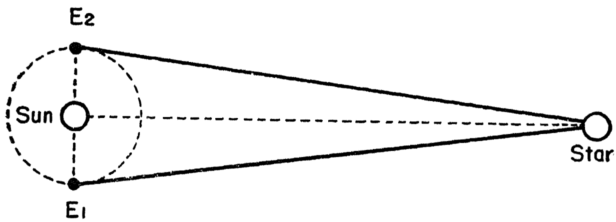


Fig. 58. Distance to star by triangulation. The angle E_1-star-E_2 is greatly exaggerated.

seconds of arc (20.5″), he was able only to conclude that the angle E_1-star-sun, which we call the ***parallax*** of the star, was less than one second. Many others attempted the experiment, and the work became more and more feverish as great improvements in experimental precision failed to show the expected parallax displacement. Several times, success was reported only to be retracted after checking of instruments revealed errors in calibration.

Finally, in 1838, Friedrich Bessel, with more refined instruments, and Struve and Henderson, independently succeeded in measuring the parallax of three stars, 61 Cygni, Vega, and Alpha Centauri, respectively. But there is no wonder that earlier observers had been disappointed—for the parallax of 61 Cygni was found to be only 0.3 second of arc. Three-tenths second of arc corresponds to the angle between the two edges of a quarter when it is placed 5 miles away from the observer!

Since then large numbers of stellar parallaxes have been measured with improving accuracy. The largest yet observed, the parallax of Proxima Centauri, is only 0.76 second of arc, which

corresponds to a distance of 26,000,000,000,000 miles. Thus even the nearest star is almost inconceivably more distant than was believed earlier. No wonder the ancients, or even astronomers up to little more than a century ago, could not see changes in star positions as the earth moved in its orbit!

Stellar Distances. Stellar distances are so great that it is almost meaningless to use miles to measure them, so we commonly use the ***light-year*** as a unit—the distance that light travels in one year at its rate of 186,000 miles per second, or about 6×10^{12} miles.[1] On this basis, even the nearest star is about 4.3 light-years distant. The light now reaching us from the nearest star started over four years ago! Sirius, the brightest star visible, is about nine light-years distant.

Parallax determinations are now commonly made by measuring the displacements of the images of brighter stars with respect to those of fainter stars on photographic plates—the faint stars are usually so much more distant that their parallax may be taken as zero for practical purposes. Actually, the image displacement corresponding to the largest parallax measured is less than one-thousandth of an inch! In the present state of the science of astronomy, stellar parallax measurements are not trustworthy for angles less than about 0.05 sec of arc—that is, for stars more than 60 light-years distant. Since most of the stars in the universe are at far greater distances than this, it was necessary to devise other methods for measuring distances to stars outside our own local part of the universe.

The Spectroscope. The spectroscope, which grew out of Newton's discovery of the dispersion of light by a prism (page 61), has since become one of the most important tools of the physicist and astronomer. In Chap. XVIII of this book we shall learn much more about this instrument and its contributions to our knowledge of the nature of matter and energy, but its influence upon astronomical methods has been so great that we shall now consider it briefly.

The plan of a simple spectroscope is shown in Fig. 59. The light beam is first made parallel by passing it through a *collimator* which consists of an opening slit and a converging lens placed at its focal distance from the slit. This parallel light is then passed through a

[1] Astronomers often use another unit—the ***parsec.*** This is the distance of a star the parallax of which is 1 sec of arc. One parsec equals 3.26 light-years.

prism, by which the different colors, or wave lengths, are deviated through different angles. Red is deviated least and violet most. These colors are then observed by a telescope. The objective lens of this telescope brings the various wave lengths to a focus each at

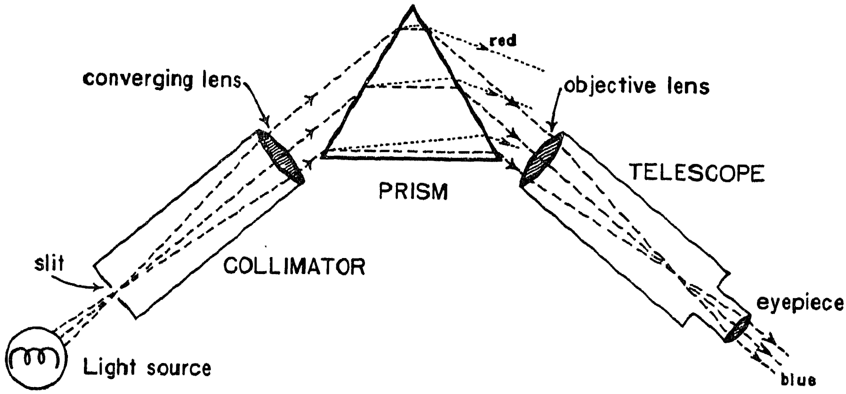


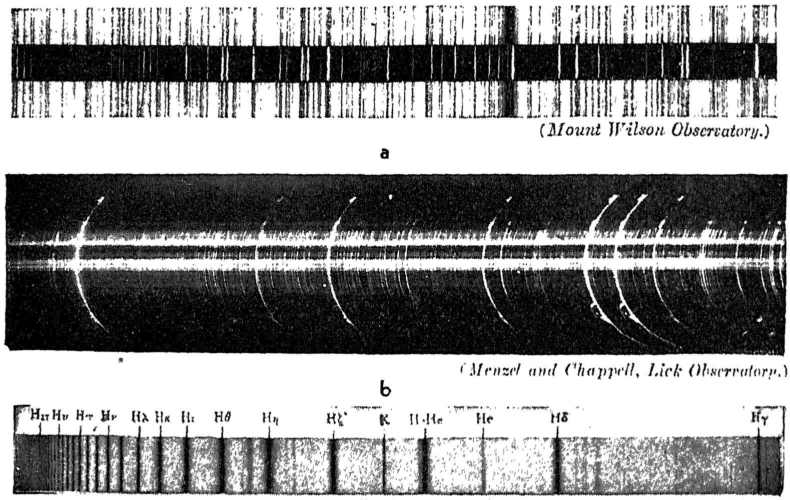
Fig. 59. Prism spectroscope.

its respective position, and thus images of the slit are formed appropriate to every wave length present in the original light—that is, we have a spectrum. The eyepiece is then used as a magnifier to examine these images. In the *spectrograph,* a sensitive plate is placed at the focus of the converging lens so that a photograph of the spectrum is taken.

Many modifications and improvements have been made in the instruments for spectroscopic investigation in astrophysics. The spectrograph was attached to the telescope to study the spectra of the planets and the stars. One of the instruments which greatly aided solar investigations was the spectroheliograph, developed simultaneously in 1891 by George Ellery Hale and Henri Deslandres. In this instrument, a moving slit was combined with a moving plate so that successive photographs of light of any given wave length emitted from various sections of the sun's surface could be made at the same time on one plate. This instrument permitted observation of distributions of different elements in the outer part of the sun.

Early investigations of the origin and nature of spectra were quickly utilized in astronomy. About 1815 Joseph Fraunhofer (1787–1826) discovered that the continuous spectrum of the sun had in it a large number of vertical black lines. He carefully observed the position of some 600 of these lines but was unable to

explain them. By 1859, Gustave Kirchhoff (1824–1887), the noted German physicist, in collaboration with Robert Bunsen (1811–1899), German chemist, set forth some of the fundamental properties of spectra, which greatly clarified the interpretation of spectro-



(*Mount Wilson Observatory.*)

a

(*Menzel and Chappell, Lick Observatory.*)

b

(*Curtiss, Detroit Observatory, University of Michigan.*)

c

Fig. 60. (a) Portion of Fraunhofer spectrum of sun (top and bottom), bright line comparison spectrum of iron vapor (middle), in laboratory. (b) Flash spectrum at total eclipse of Aug. 31, 1932. (c) Spectrum of the star Zeta Tauri showing remarkably fine series of hydrogen absorption lines on continuous background.

scopic studies. There were found to be three major classes of spectra:

1. Bright-line Spectra. The luminous gas or vapor of an element[1] under low pressure gives spectra which consist of individual bright lines. Each element emits its own characteristic lines of definite wave length. The analysis of bright-line spectra is a most powerful method for identifying the elements present in an object on earth, or in the stars.

2. Continuous Spectra. An incandescent solid or liquid or a gas under high pressure produces a continuous spectrum, a continuous band of color from red through orange, yellow, green, blue, and violet. The intensity of the different wave lengths emitted is determined by the temperature. The study of continuous spectra has been exceedingly important in investigating stellar tempera-

[1] All matter found in nature is composed of some 88 elements which cannot be further decomposed by ordinary physical or chemical methods (see p. 180).

tures. (We shall postpone consideration of the method by which this is done until Chap. XVIII.)

3. Absorption Spectra. Kirchhoff discovered that if light from a high-temperature source of continuous radiation passes through a layer of gas at lower temperature, the cooler gas absorbs many of those same characteristic wave lengths of light which it would emit if it were radiating. The dark Fraunhofer lines could then be explained—they were caused by the cooler layers of gaseous elements in the outer parts of the sun's atmosphere, each of which absorbed its own characteristic wave lengths from the continuous spectrum of light emitted by the incandescent central part of the sun. These Fraunhofer absorption lines were soon found to correspond in wave length to bright-line spectra of the various common elements: sodium, iron, calcium, copper, oxygen, hydrogen, etc. These elements were thus discovered to be common to earth and sun.

Spectroscopic investigations of the sun during an eclipse in 1868 showed a strong yellow line that had never before been observed. Astronomers reasoned that this must be from an element present only on the sun, and named it helium. Not until 1895 was the element helium discovered by Sir William Ramsay, right here on earth! It was a great victory for spectroscopic methods.

The Spectroscope Measures Velocity. The spectroscope may be used to determine the velocity of a source of light. No doubt all of us are familiar with the sudden lowering in pitch of the whistle of a moving locomotive as it passes us. The apparent decrease in pitch (or increase in wave length) when the source which first approaches us starts to recede is known as the Doppler effect, and occurs with light as well as sound.

The fractional change in wave length of light, due to a velocity v of the source with respect to the observer, is just the ratio of v to the velocity of light, V. Algebraically this can be stated

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{V}$$

Here $\Delta\lambda$ is a symbol for the ***change*** in wave length due to the relative motion of the source and observer, λ is the normal wave length of the light, and V, the velocity of light, is 186,000 miles per second. Thus, from a measurement of $\Delta\lambda$, v, the velocity of the source, may be determined. Expressing this differently: if the distance between the observer and the source is increasing, the spectral lines of the

source are shifted toward the red (or longer wave length). If the distance is decreasing, the spectral lines are shifted toward the violet; the shift in each case is proportional to the velocity.

The spectroscope, therefore, makes it possible to determine the composition, the temperature, the direction of motion, and the speed of a star. Many other special instruments, such as the thermocouple and photoelectric cell, have been used by the astrophysicist for measuring star temperatures and relative brightness. We can see that the story of astronomical discovery becomes more and more involved as the techniques of the astronomer, physicist, and chemist are merged.

THE SOLAR SYSTEM

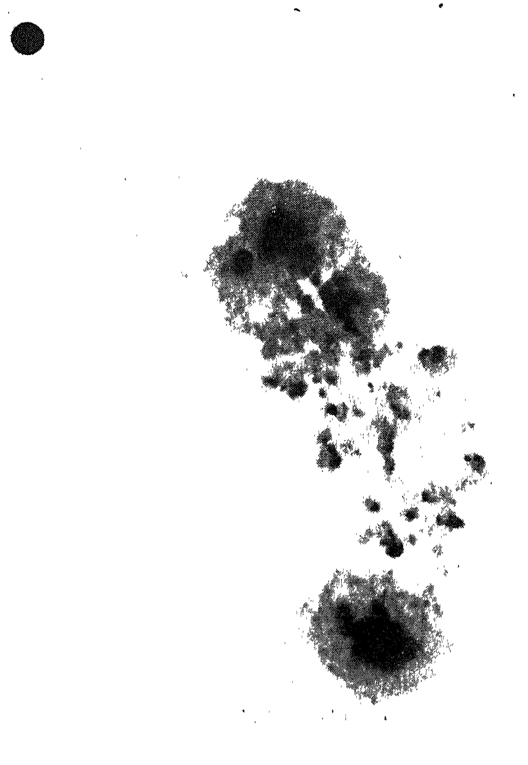
In our glimpse of the gradual development of man's ideas concerning the universe, we have already learned something about the nature of the earth, sun, moon, and planets, which, with various smaller bodies, make up our solar system. Now let us consider in more detail what the new methods and the patient effort of many men have contributed to our knowledge of the solar system and of its place in the universe.

The Sun Is Our Nearest Star. The sun is certainly to us the most important celestial body. Not only does it control the motion of the earth and other planets, but all forms of life owe their very existence to the energy it radiates. The sun is the direct or indirect source of virtually all the types of energy that man utilizes on earth—our light and heat, food, oil, coal, water power, etc. The whole character of the earth, its surface changes, in fact, nearly all the phenomena in nature have been and continue to be profoundly influenced by the sun.

This star, which we call our sun, is just an average sort of star as far as brightness, temperature, size, and composition are concerned. As its distance from the earth is but 93 million miles, we have been able to study it easily and so obtain much detailed information about stars in general. The sun is 864,000 miles in diameter, 109 times the diameter of the earth. This distance takes on significance when we realize that it is almost four times the distance from the earth to the moon. The sun has nearly 1,300,000 times the volume of the earth, although its mass is but 330,000 times that of the

earth; therefore it is only one-fourth as dense. It comprises, however, 97.7 per cent of the total mass of our entire solar system.

The Photosphere. The sun's temperature is higher than the vaporization point of all known substances, even the most refrac-



(*Mount Wilson Observatory.*)

Fig. 61. Great sunspot group. Disk represents size of earth.

tory metal. In other words, the sun is a hot, gaseous sphere. All known evidence corroborates this conception of its nature.

Because its density decreases regularly from the center toward the outer region, the sun does not have a sharp, definite surface. We see, however, an apparent surface which is called the ***photosphere*** (light-giving sphere). It is the region where the density and temperature are high enough so that the gases are no longer transparent. The effective temperature of the photosphere is about 6000°C (centigrade) or 10,000°F (Fahrenheit).

Sunspots and Solar Storms. The sun's photosphere has a mottled, grainy appearance marked by occasional dark areas which range from mere specks 300 miles across (about the smallest visible) to great groups 100.000 miles or more across. These sunspots are

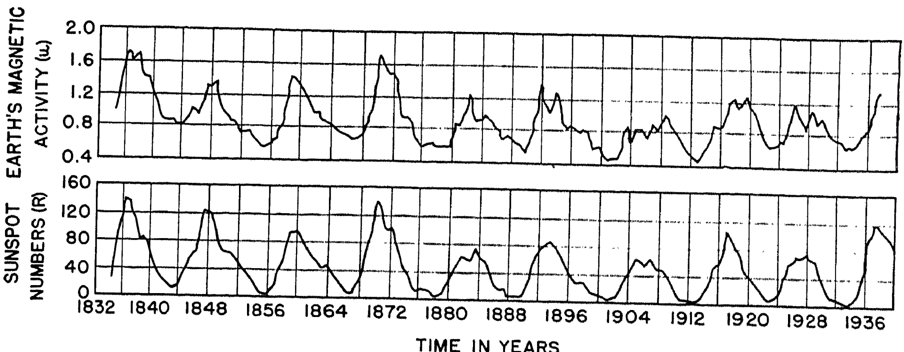


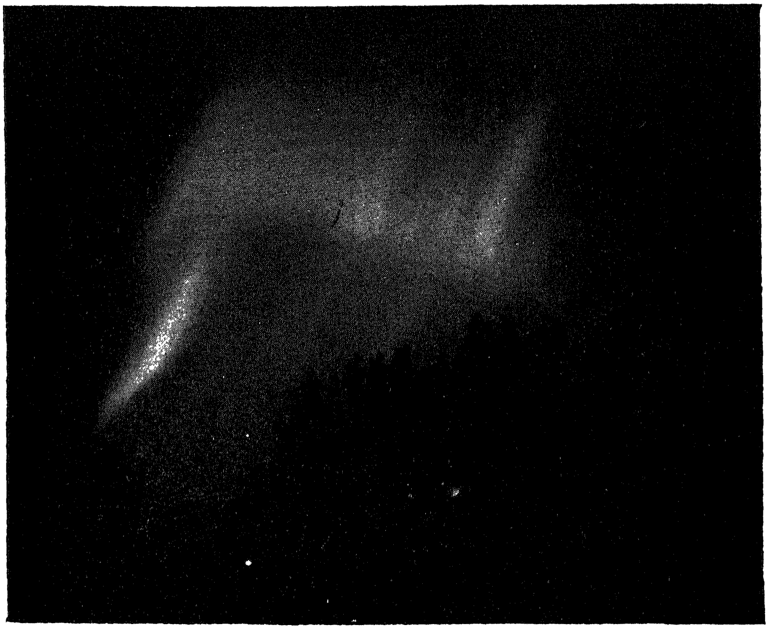
Fig. 62. Sunspot cycles. There is a close correlation between the upper curve representing disturbances of the earths' magnetic field and the curve determining numbers of sunspots. (Data from the Smithsonian Institution.)

simply great cyclonic storms in the sun's atmosphere, which whirl much like terrestrial cyclones and disturb the gases so that the pressure and temperature are markedly reduced. Actually the temperature of a sunspot is usually around 4000°C, which is even hotter than an arc light, so the sunspot appears dark only by contrast with the rest of the sun's photosphere (6000°C). The motion of sunspots provides one method of studying the rotation of the sun near its equator; no spots appear near the poles. The sun rotates from west to east like the earth, although it is unlike a solid body, for the spots near the sun's equator appear to make a complete circuit in about 25 days, while other evidence shows that the period of rotation near the poles is more nearly 34 days.

The number of visible sunspots varies from day to day. Most of them last from one to four days although a few of the large ones last more than a month. The variation in the average number of spots from year to year is quite marked, and clearly shows successive maxima about 11 years apart (Fig. 62).

Do Sunspots Affect Conditions on Earth? Many attempts have been made to correlate sunspot variations with all sorts of events here on earth, from the weather to depressions and wars. There is certainly a close connection between sunspot activity and the occurrence of the *aurora borealis*, or "northern lights," and also

the terrestrial magnetic storms which are occasionally strong enough to interfere seriously with telegraph, telephone, and radio communication. One suggestion is that the whirling vortices of the sunspots, which are known to be associated with enormous mag-



(*Photographic Atlas of Auroral Forms. Courtesy of The Sky.*)

Fig. 63. Aurora.

netic fields, expel great streams of electrons which produce electrical disturbances in the upper atmosphere when they pass into the earth's magnetic field.

The correlation between number of sunspots and weather is so inconclusive that scientists at the Smithsonian Institution and elsewhere are still studying the problem. Most of the other attempts to correlate sunspots and terrestrial phenomena are either preliminary speculation or sheer nonsense.

The Reversing Layer. The reversing layer is the name given to the region, about 1,000 miles thick, in the solar atmosphere just above the photosphere. This layer of low-pressure gases is responsible for the dark lines discovered by Fraunhofer in the solar spectrum. As we have learned from the researches of Kirchhoff and Bunsen, a region of high-pressure gases at high temperature, such as the photosphere, emits a continuous spectrum containing all

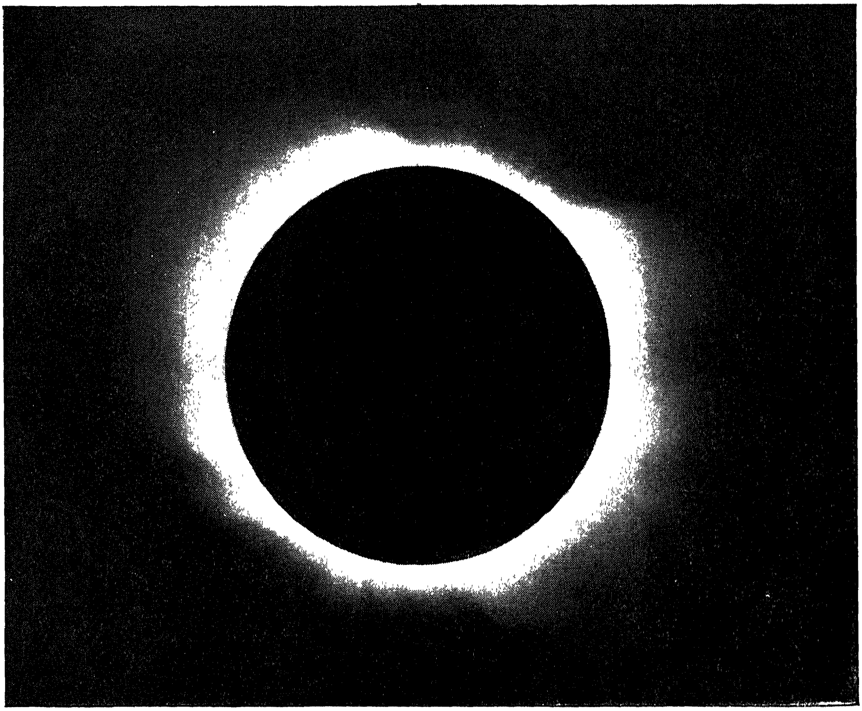
the colors and no lines. When this light, on its way to us, passes through the less dense, cooler gases in the reversing layer, these gases absorb precisely those wave lengths of light which they would emit at higher temperatures. Thus, in the solar spectrum,

(*Mount Wilson Observatory.*)

Fig. 64. Prominence of sun 140,000 miles in height. Small disk represents size of earth.

dark absorption lines appear that correspond to elements present in the reversing layer.[1] These lines may be matched with the bright lines emitted by various elements here on earth, and as a result more than 58 of the 90 known elements have been identified in this layer. The gases in the reversing layer are of course hot enough to emit some light themselves. The normally dark lines therefore can be observed as a bright-line spectrum for a second or two dur-

[1] See Fig. 60 (a), p. 87.



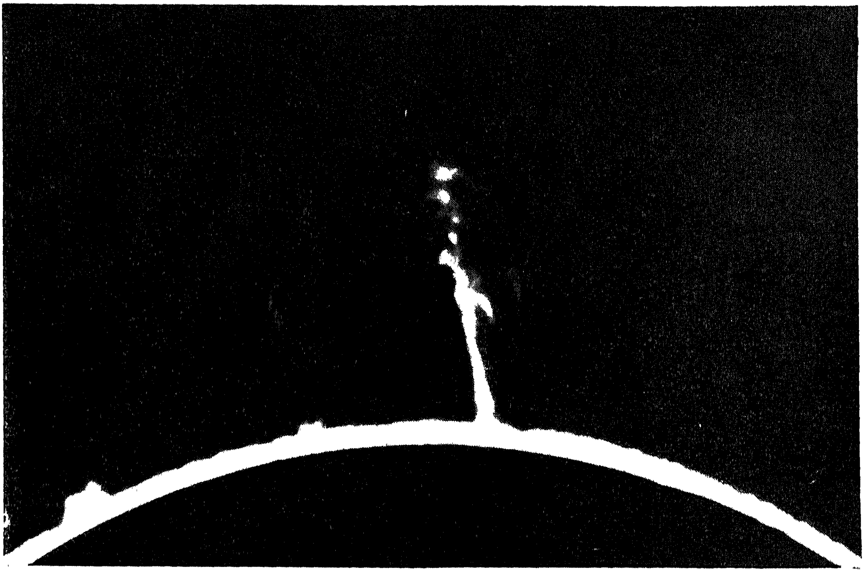
(*Yerkes Observatory.*)

Fig. 65. Sun's corona photographed during a total eclipse, May 28, 1900. Notice streamers from poles of sun.

ing a total eclipse, when the bright light from the chromosphere is blocked out by the moon's disk. This is called the "flash spectrum" (Fig. 60b).

The Chromosphere. The chromosphere (color sphere) is the next of the arbitrary divisions in the sun's atmosphere. It is just outside the reversing layer and extends perhaps 6,000 miles, although it has no definite boundary. Here the gases are at very low pressures and about 4000°C. The chromosphere contains mostly hydrogen, helium, and calcium, thus producing dark absorption lines in the solar spectrum corresponding to these elements. Eruptive disturbances often project from the chromosphere immense clouds of luminous gas, called ***prominences,*** to heights as great as 500,000 miles.

The Corona. During eclipses another region called the ***corona*** appears as a beautiful halo of pearly white light. It is so faint compared to the photosphere that it cannot be seen except at



(*Wide World.*)

Fig. 66. Solar "tornado" 150,000 miles high. Photographed at Mount Wilson with disk producing artificial eclipse.

totality. The gases of the corona are at extremely low pressure, and their temperature is less than 2000°C. Often eclipse expeditions travel great distances to regions where a total solar eclipse is to occur in order to obtain valuable data on the corona and the "flash spectrum." During a recent eclipse, streamers in the corona were observed to extend out at least 20 million miles from the sun, a distance of more than twenty times the sun's diameter. The gases in this region are so rarefied that they offer no apparent resistance to comets which pass through them.

It is interesting to note that scientists of the Bell Telephone Laboratories recently have devised a system called the "coronavisor" which utilizes television methods to make possible the study of the corona in full sunlight. A small black disk just the size of the sun's image is used to blot out the main light from the sun. The faint corona at the edge of the sun is then viewed by television techniques in order to eliminate the comparatively steady effects of stray light which would otherwise still obscure the corona. Such methods promise to accelerate greatly many studies that previously could be made only during total eclipses.

Source of the Sun's Energy. The sun, like all stars, radiates energy in the form of light at an enormous rate. Each square inch

of the sun's surface is radiating energy continuously at the rate of about 60 horsepower. Our tiny earth is so very distant that it receives only about one part in 2 billion of the total energy that the sun gives off. Yet if the solar radiation that strikes the earth in a single minute were all converted into electric energy it would be worth about 25 billion dollars even at one-quarter the normal residence rate of most power companies.

What is the source of this tremendous quantity of energy that the sun has been pouring off into space for at least 2 billion years? Astronomers and physicists have been searching for the answer for many years. Only recently have they made progress toward understanding the processes and conditions in the sun which result in this great energy liberation. The results of present-day "atom-smashing" experiments have revealed much about the possible explanation. We shall need to learn a great deal more about the nature of matter, energy, and radiation before we can begin to appreciate this question, so we shall defer the problem until later (Chap. XXI). For the present let us say that the temperature at the center of the sun is estimated to be about 20,000,000°C, or 40,000,000°F, and the pressure is probably near 15 billion pounds per square inch. Under such extreme conditions matter indeed may be converted into energy!

The sun's mass is actually being destroyed and energy radiated. Fortunately for our descendants, such processes are so efficient that up to now the sun has probably lost only a small fraction of its original mass and it should last many billions of years.

The Planets and Their Satellites. The relative distances of the planets from the sun and the relative sizes of the planets are shown in Fig. 67. The distances are given in ***astronomical units:*** one astronomical unit equals the mean radius of the earth's orbit, or 93 million miles. The length of the year is given for each planet in terms of earth's year. The slightly elliptical orbits all lie very nearly in one plane, and all the planets revolve about the sun in the same direction. All but Uranus rotate about their own axes from west to east. A summary of the information about the planets appears in the table on page 115.

Mercury. The diameter of Mercury, smallest of the planets, is only 1.5 times that of the moon, or about 3,100 miles. Mercury, whose name meant to the Greeks "messenger of the gods," is just

36 million miles from the sun, and as we might expect from Kepler's laws it literally races around its orbit in only 88 days. Its orbit is one of the most elliptical, having an eccentricity of 0.206. The planet's nearness to the sun makes observation impossible except

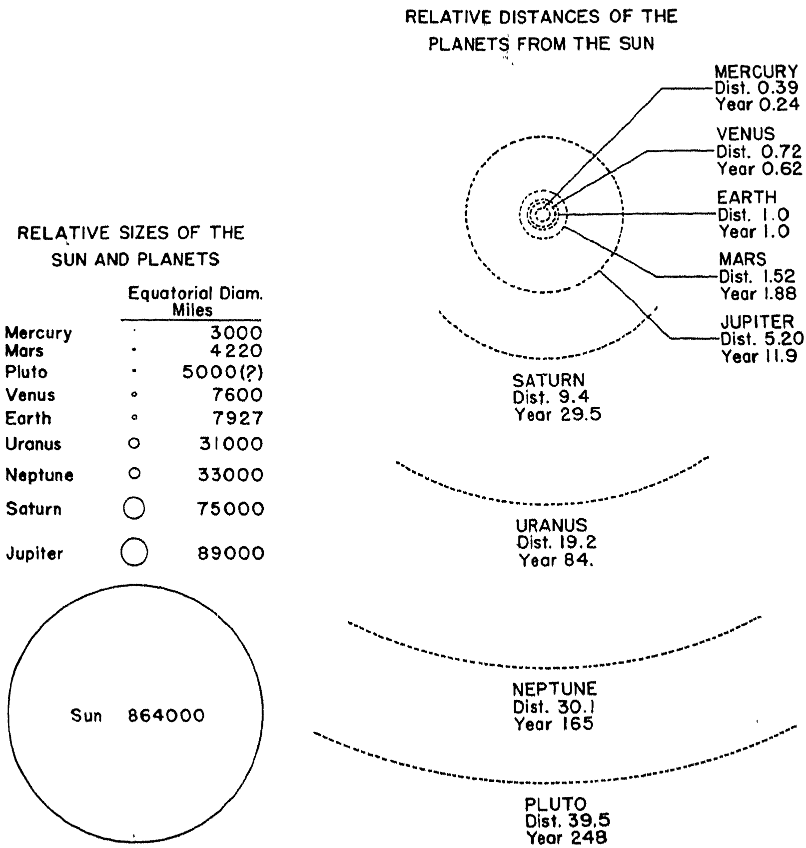


Fig. 67.

when it is in certain favorable positions, but what evidence there is indicates that tidal friction has slowed Mercury's rotation until its day is the same length as its year. This means that the same side is always turned toward the sun. This planet is so small that its gravitational attraction is not sufficient to hold gases to its surface, so it has no protective atmosphere. The sun's rays beat down on Mercury more than seven times as intensely as on earth; hence the side facing the sun scorches at temperatures of nearly 700°F, so that the only possible oceans would be of molten lead or sulfur.

The other side of the planet remains continuously frozen. Like all the other planets, Mercury shines only by reflected sunlight.

Venus. Our nearest neighbor, Venus, is at times the brightest object in the sky except for the sun and moon, yet we know little about it. Venus is almost the twin of the earth in many ways. Slightly less in size (7,600 miles in diameter), it is 67 million miles from the sun. Its year is 225 of earth's days. Like the earth, it has an atmosphere, but since heavy clouds continually hide the surface from view we do not even know the length of its day. Strangely enough, spectroscopic investigations show that hardly more than a minute trace of free oxygen can be present in the atmosphere of Venus, whereas recent work indicates that carbon dioxide probably occurs in more than 10,000 times the concentration on earth. These conditions might be expected because oxygen is so active chemically. There would probably be little free oxygen on earth either were it not for vegetable life. Water vapor also does not seem very abundant in the atmosphere of Venus, but the tests for it are not very sensitive. The temperature on Venus must be slightly higher than on earth. Although climatic conditions are favorable, we must conclude that the absence of oxygen shows that life has not developed on Venus, certainly not in any form we know.

Earth. Our earth is a very commonplace planet astronomically speaking, but it may be unique in that it supports life. Its orbit is almost circular (eccentricity only 0.017), so its distance from the sun is always within about 1,000 miles of the mean radius of its orbit (93 million miles). The earth travels about 1,000 miles per minute in its annual journey of 580 million miles around the sun.

If from Venus one could see through the thick clouds which cover that planet, the earth would probably be called a "double planet," for the moon, with a diameter of 2,160 miles, is much nearer the size of the mother planet than are the satellites of other planets—it measures more than one-quarter the diameter of the earth. From Venus, the moon would be seen to revolve about the earth at a distance of 240,000 miles once every 27⅓ days,[1] both earth and moon circling the sun in 365¼ terrestrial days. With a good telescope, one could see from Venus the polar ice caps, the continents and oceans of the earth, the green vegetation of its

[1] To us the moon has an *apparent* period of 29½ days because the earth's position in its orbit changes so that the moon when lined up between earth and sun must make more than a full revolution before it will again be in line between earth and sun.

temperate and torrid zones, and its mountains and deserts. This observer would notice that the earth is slightly flattened, being 7,927 miles in diameter at its equator and 7,900 at the poles.

The axis of the earth is inclined 23½ degrees from the per-

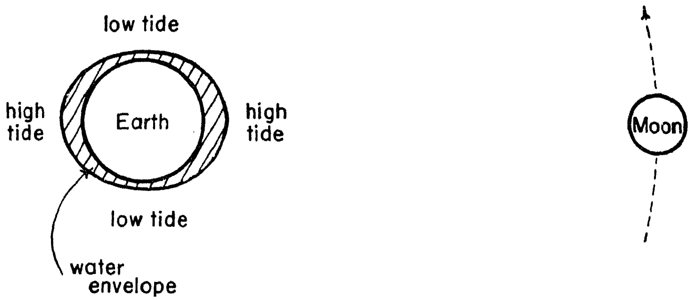


Fig. 68a. Tides result because gravitational attraction of the moon is greater at the earth's near surface than at the far surface.

pendicular to its orbit, and this, as Copernicus showed, is the cause of the seasons. Hipparchus, we have learned, was the first to discover that the earth's axis traces out a cone, or "precesses" (Fig. 14). The axis now points toward Polaris—the polestar—but 13,000 years from now it will point to the star Vega, and in 26,000 years back to Polaris again.

Further material about the earth, its crust, and its life belongs to other sections of the science program.

Our Moon. Our moon is only $\frac{1}{400}$ the diameter of the sun, but because it is about 400 times nearer to us, the two seem to be approximately the same size. Since its mass is about one-eightieth and its radius about one-fourth that of the earth, by applying Newton's law of gravitation we can see that the gravitational attraction on the moon's surface would be about one-fifth that on the earth. A man weighing 180 lb on the earth would weigh only 36 lb on the moon! If we could visit the moon it would be an interesting experience, but not a very pleasant one, for we would find a literally dead world. The moon has no atmosphere because, like Mercury, its gravitational attraction is too weak to hold gases to its surface, and of course it has no water. Long ages ago the gravitational force exerted by the earth on the moon, combined with tidal friction in the then plastic moon, gradually slowed or "braked" the moon's rotation until it was "caught" in the earth's gravitational field. Now it always keeps the same face turned toward us. Small irregular motions called ***librations*** permit us to

see a little around the moon's edge, but four-ninths of its surface will doubtless be invisible forever.

In accordance with Newton's statement that all forces exist in pairs,[1] the moon's gravitational attraction also affects the earth

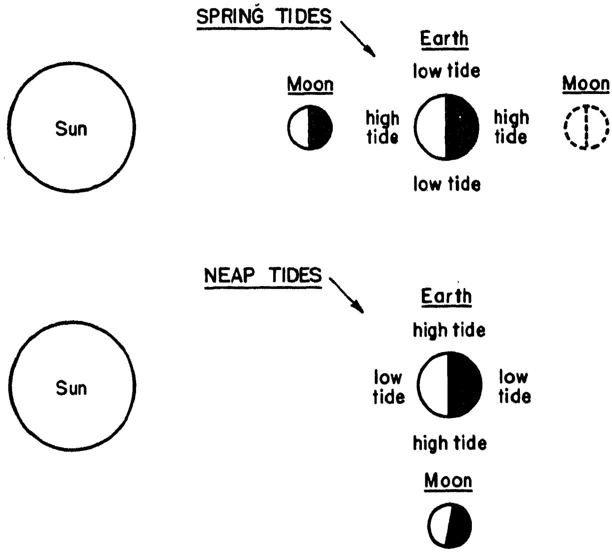


Fig. 68b. "Spring tides" occur when the effects of sun and moon add. "Neap tides" occur when the effect of the sun partly counteracts that of the moon.

and causes the familiar tides in the terrestrial oceans, and even small but measurable tides in the earth's solid crust. As the sun produces a smaller though appreciable tidal effect, our highest tides, the "spring" tides, occur when the moon and sun appear to be nearly together (in conjunction) or else on opposite sides of the earth (in opposition).

The moon shines because the brilliant sun illuminates the side that faces it, leaving the other side in darkness. The merciless beating of the sun on one region for a full two weeks raises the moon's surface temperature above the boiling point of water (212°F), since there is no protective atmosphere or ocean to equalize temperatures. During the long lunar night, the dark side becomes exceedingly cold, probably about −240°F.

Phases. One of the most striking lunar phenomena is the changing of the moon's phases. The reason for this is very simple and is illustrated in Fig. 69. The relative sizes of the moon and the

[1] See Newton's third law, p. 58.

earth are necessarily exaggerated as compared with their distance apart. Because of the orbital motions of the moon around the earth and the earth around the sun, the relative positions of all three bodies are constantly changing. When the moon is in position *A*

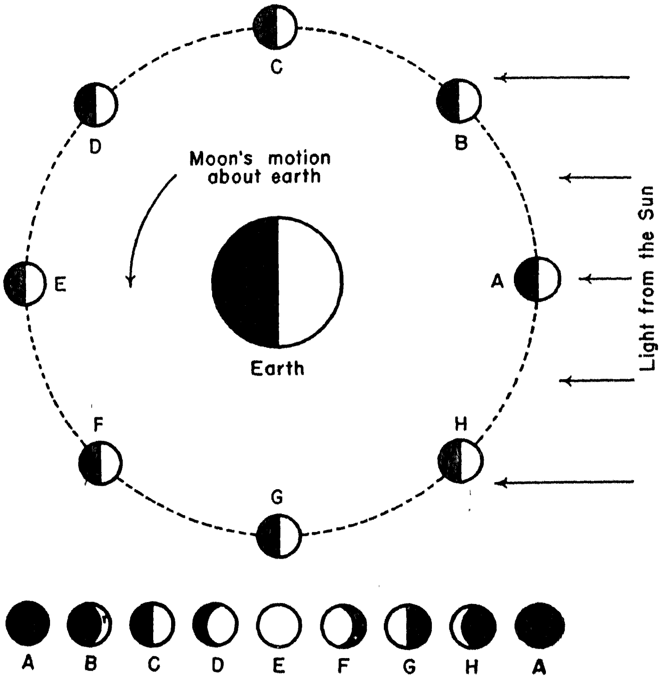
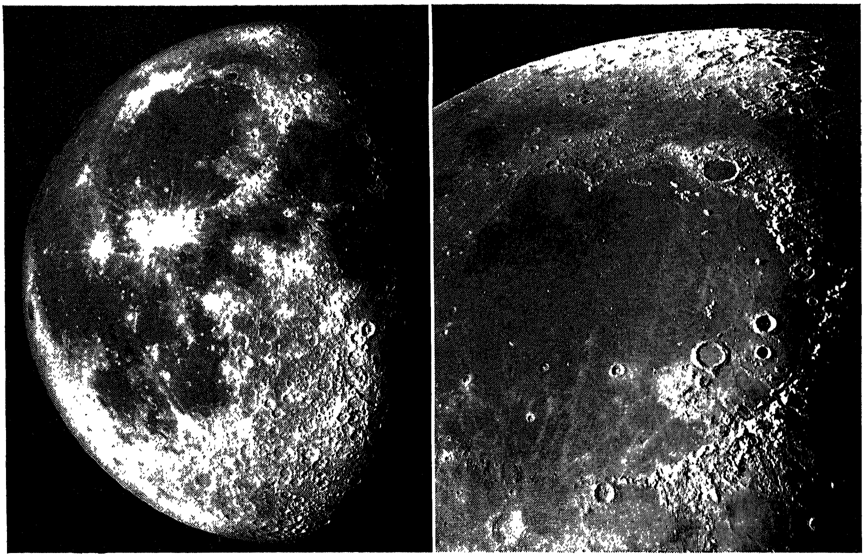


Fig. 69. Phases of the moon.

we cannot see the illuminated side, and we call it ***new moon.*** A few days later, at *B*, we see a small part of the moon and call it the ***crescent*** phase. At *C* we see half the moon's surface illuminated and call this the ***first quarter.*** At *E* we see the entire disk illuminated—***full moon.*** From full moon the moon begins to wane. We then have ***third quarter*** at *G*, and so back to new moon again at *A*. Mercury and Venus, having orbits smaller than the earth's, also exhibit "phases."

The total lunar period of about 29½ days made a natural division of time, and the words "moon" and "month" had a common origin in ancient languages. Many superstitions still center about the moon and its phases, even in this "age of enlightenment." Most of them, such as the value of planting in the "dark of the moon," have no foundation whatever. However, there is



(a) (b)

(*Mount Wilson Observatory.*)

Fig. 70. The lunar surface. (a) At phase F of Fig. 69 with 60-in. reflector. (b) Detail of upper part of (a) with 100-in. reflector.

some truth in the one that says that a ring around the moon means wet weather, for such a "ring" is caused by large amounts of moisture in our atmosphere.

The Lunar Surface. Even a small telescope reveals much of the barren beauty of the lunar landscape. Great mountain ranges,

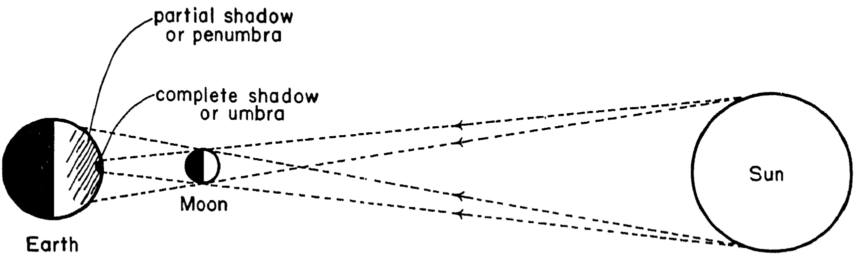


Fig. 71. Solar eclipse. The relative distances and sizes are of course not accurate.

huge craters, and desolate plains stand out, especially when the sun shines at an angle to the surface so that the shadows give the effect of perspective. Since wind and moisture are absent on the moon, no erosion occurs, and the rough, jagged contours are preserved as they were made. The origin of the lunar craters, some of which are

over 100 miles across, is a debatable point. One theory is that they are due to the impact of large meteorites, and indeed they resemble the famous crater left by a meteor in Arizona. However, it seems unlikely that the random impact of meteors would leave so many craters in some regions and virtually none in others. Another theory is that they are craters of extinct volcanoes, but only tremendous volcanic activity would have produced so many of the huge craters. Although there is no evidence of lava flow, recent studies of reflection from the moon's surface have led to the belief that it is covered with a material similar to volcanic ash.

Eclipses. A ***lunar eclipse*** may occur when the moon is full (at position E in Fig. 69), for then the earth may come directly between the moon and the sun, and the earth's shadow will fall on the moon. Similarly a ***solar eclipse*** may occur when the moon is new (at position A), for then the moon may come between the earth and the sun, and the shadow of the moon will fall on the earth.

Why is it, then, that we do not have eclipses at every full and new moon? Eclipses seldom occur because the moon's orbit is inclined 5 degrees to the earth's orbit and the distances are so great that only rarely are the sun, earth, and moon really in line so that an eclipse can occur.

It was known in early times that both lunar and solar eclipses follow a definite schedule. Eclipses of the same type always recur at intervals of 18

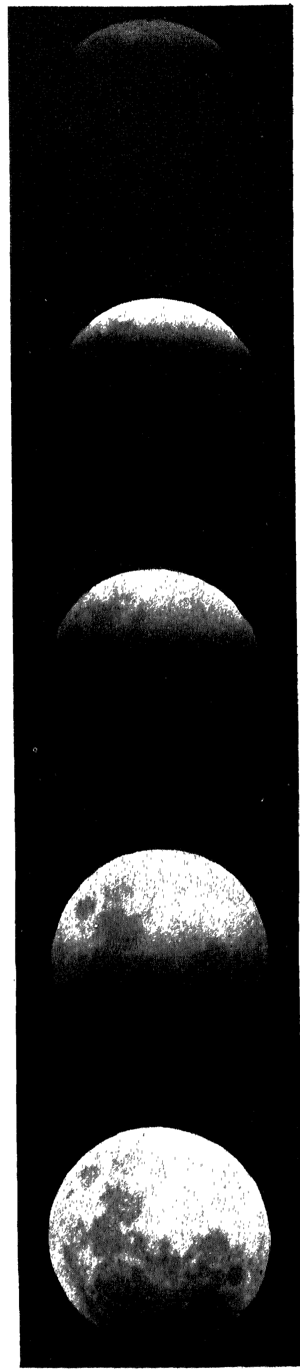


Fig. 72. Progress of lunar eclipse during one hour.
(Photographed with 6-in. telescope by Charles A. Federer, Jr., and Robert G. Cox. Courtesy of The Sky.)

years, $11\frac{1}{3}$ days.[1] There are from two to five partial solar eclipses per year and usually one solar eclipse that is total somewhere on earth occurs every year and a half. To foretell the exact time and path of the rapidly moving circular shadow of the moon across the earth's surface requires very accurate calculation. Nevertheless its position can be determined within 1,000 ft.

Mars. Just outside the earth's orbit is fire-red Mars, named for the Greek god of war. It is 142 million miles from the sun and therefore has a fairly long orbital period—687 of our days. Its day is $24\frac{1}{2}$ hours. Two small moons circle about Mars; these were discovered in 1877, although it is interesting to note that three centuries ago Kepler, in a letter to Galileo, expressed his belief in their existence. As the diameter of Mars is about one-half that of the earth, its mass is much less; nevertheless the planet has been able to hold some atmosphere.

The thin atmosphere permits telescopic observation of Mars' surface features, and its strange markings have given rise to many fantastic stories. Polar ice caps are clearly present, indicating that there is some water. Red desert regions and gray-green areas appear, and both of these are criss-crossed by a network of lines which the late Percival Lowell called "canals." Does life exist on Mars? Are these lines actually canals built by intelligent beings to bring water from the ice caps? These interesting speculations are difficult to answer. The temperature on Mars is somewhat lower than on earth; moreover, the oxygen and water content of the atmosphere is low. Life, if it did exist, would have adapted itself to conditions very different from those on earth. Seasonal variations in size, shape, and color of the gray-green markings do occur, so it is probable that some types of plant life exist. However, it is likely that the so-called canals are strips of vegetation along river beds, rather than the stupendous engineering feats of superbeings.

The Asteroids. The solar system contains many small fragments of rock and metal which transverse orbits in the sun's gravitational field. A group of comparatively large pieces of matter have orbits most of which lie between Mars and Jupiter. Ceres, the largest of these so-called minor planets, is about 500 miles in diameter. It was discovered in 1801. Such bodies are discovered by searching

[1] This figure assumes the inclusion of four leap years; it should be 18 years, $10\frac{1}{3}$ days if there are five.

for faint "stars" that make streaks or trails on photographic plates while the true stars are made to "stand still" by moving the telescope to compensate for the earth's rotation. Over 1,500 of these asteroids are now known, the smallest probably less than five miles in diameter. Of course, an almost infinite number of smaller particles is also present.

Jupiter. Jupiter is the largest of all the planets. Its diameter is 88,000 miles, eleven times that of the earth. As its density is much less than the earth's, its visible globe is probably partly gaseous. It whirls so rapidly on its axis—its day is 10 hr—that it bulges more than the earth at the equator owing to centrifugal force. The Jovian year is almost 12 of our years, as we would expect because of its distance from the sun—483 million miles. Recent measurements show that its temperature is low, possibly −220°F, so all water must be frozen. Its atmosphere is largely methane (marsh gas) and ammonia. As we learned earlier, Römer used the time schedule of two of Jupiter's eleven moons to make the first determination of the velocity of light.

Saturn. When Galileo first looked at Saturn with a telescope he observed some queer appendages, but it was not until 1655 that Huygens discovered that this planet is completely surrounded by a series of broad, flat rings. This remarkable ring system is one of the most beautiful sights in the heavens. The period

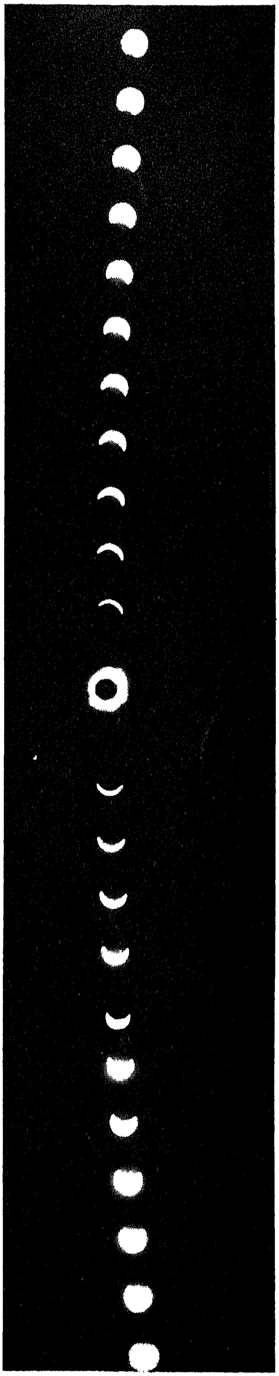
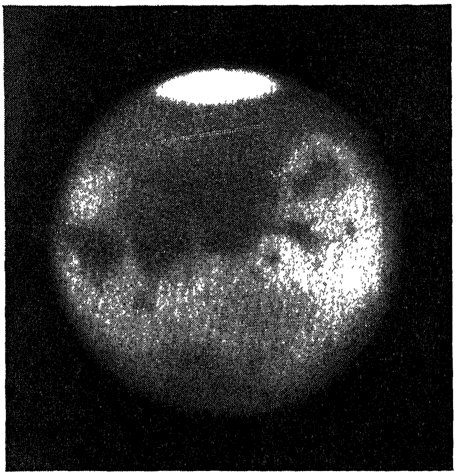


Fig. 73. Eclipse of the sun—from beginning to end. Exposures were made at intervals of 5 min. The central exposure showing the corona was much longer than the others. *(Photographed by National Geographic, U. S. Navy Expedition to Canton Island in the mid-Pacific, June 8, 1937.)*

of Saturn around the sun is 29½ years. Twice during each period Saturn's rings are edgewise to use; they then become nearly invisible for a day or two, showing that they are less than 50 miles thick! James Clerk Maxwell, a physicist of whom we shall hear much more,



(*E. C. Slipher, Lowell Observatory.*)

Fig. 74. Mars, showing surface details. E. C. Slipher, expedition to the Lamont-Hussey Observatory, Bloemfontein, South Africa (1939).

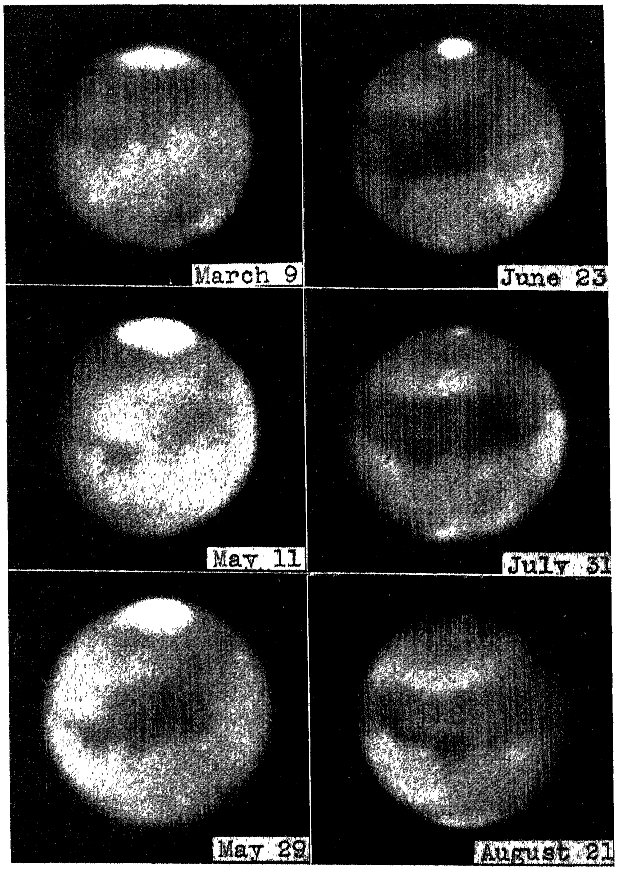
gave the accepted explanation of them in 1856 when he showed that only rings composed of a swarm of particles such as meteors going around Saturn like moons would be as stable as these rings appear to be. Saturn itself cannot be very solid, for its density is less than that of ice. Its atmosphere is similar to Jupiter's. The orbit of Saturn is nearly 900 million miles from the sun and is the outer boundary of the solar system known to the ancients.

Uranus. Beyond Saturn, no planets are visible with the unaided eye, except Uranus under ideal conditions. Uranus was not discovered until one of Herschel's reflectors picked it up in 1781. About 1,780 million miles from the sun, nearly twenty times the earth's distance, Uranus travels around the sun in 84 years. Its diameter is 31,000 miles, and, as it is only fifteen times heavier than the earth, its density is not much more than that of water.

Uranus is interesting chiefly because it is the only planet that rotates from east to west. Its axis, however, is tilted so much (82 deg) that this planet almost "rolls" along its orbit. This non-

conformity of Uranus somewhat disturbs theories about the origin of the solar system.

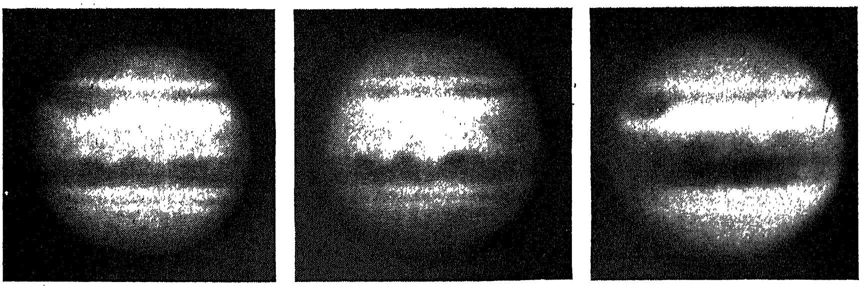
Neptune. The orbit of Uranus was calculated from the early observations, on the basis of Newton's laws. By 1840, in spite of



(*E. C. Slipher, Lowell Observatory.*)

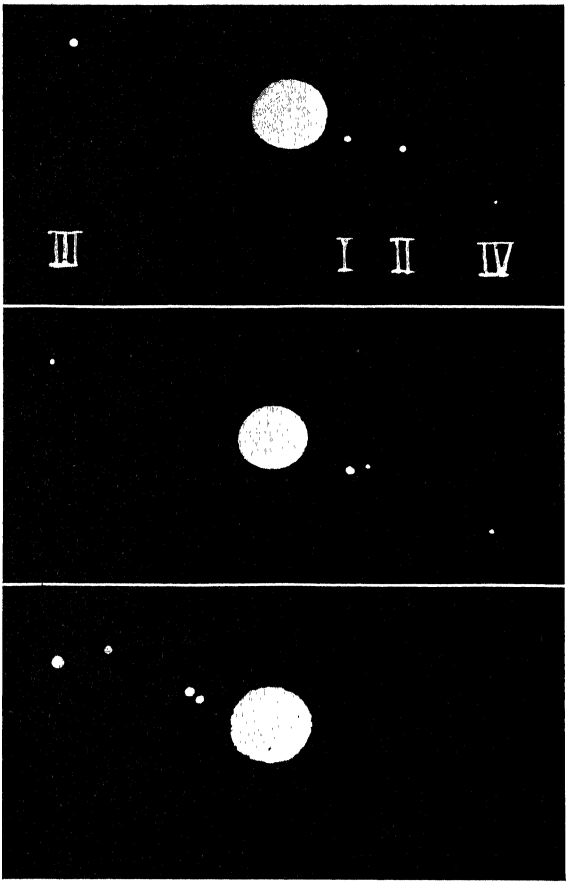
Fig. 75. Mars's seasonal changes. Photographs of the same face of Mars at different Martian seasonal dates showing the gradual melting of the snow cap and intensification of the dark blue-green areas from Mar. 9 to Aug. 21 (Martian dates). The development of the blue-green areas during Martian summer strikingly matches the behavior of growing vegetation.

all attempts at correction and refinement, the discrepancy between the actual position and calculations, though only about thirty times the diameter of Uranus, was sufficient that astronomers felt certain something was amiss. It was a serious dilemma: either the



(*E. C. Slipher, Lowell Observatory.*)

Fig. 76. Jupiter photographed by green (left), red (center), and blue (right) light. The "Great Red Spot" shows dark in the blue image and can hardly be seen in the red image.



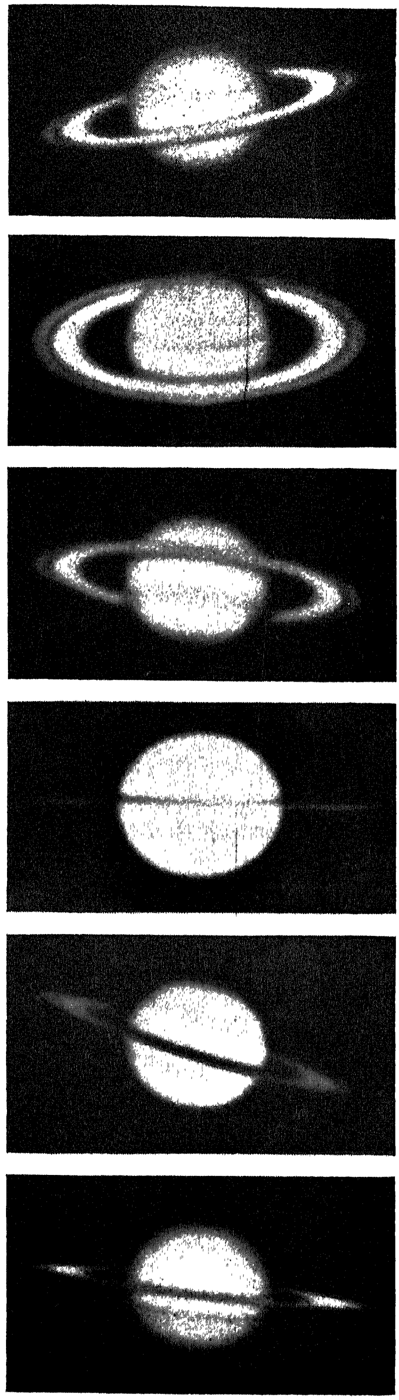
(*Yerkes Observatory.*)

Fig. 77. Jupiter—showing change in position of four satellites.

whole system of Newtonian mechanics was wrong or some other influence had to be found. Adams in England and Leverrier in France spent much time on the problem, and about 1845 both concluded independently that the simplest explanation was that the motion of Uranus is disturbed by a still more distant planet. Their calculations of its position agreed well, and finally astronomers at Cambridge were persuaded to look for the expected planet. The search progressed so slowly that in 1846 Leverrier prevailed on Dr. Galle at the Berlin observatory to help with it. Galle found the new planet in less than an hour, within 1 deg of the predicted location!

It was a great triumph for mathematical astronomy to discover a new world 2,800 million miles out in space. Neptune takes 165 years to make its revolution about the sun, and 16 hr to rotate on its axis. It has only one moon.

It is of interest that Neptune would have been discovered 50 years ahead of time if Lalande of the Paris Ob-



1909

1917

1934

1936

July, 1937

Oct. 1937

Fig. 78.—Saturn. Views from 1909 to 1937. The rings appeared edgewise in 1936. They were dark in July, 1937, and bright in October because of different relative positions of the sun.

(*E. C. Slipher, Lowell Observatory.*)

servatory had shown more confidence in his observations. In 1795, two of his determinations of position of a star did not agree, so Lalande arbitrarily threw one out. Now it is known that this "star" was actually Neptune—had Lalande checked its position he would have found that its "wandering" was real and that he had had the rare opportunity to discover a new planet.

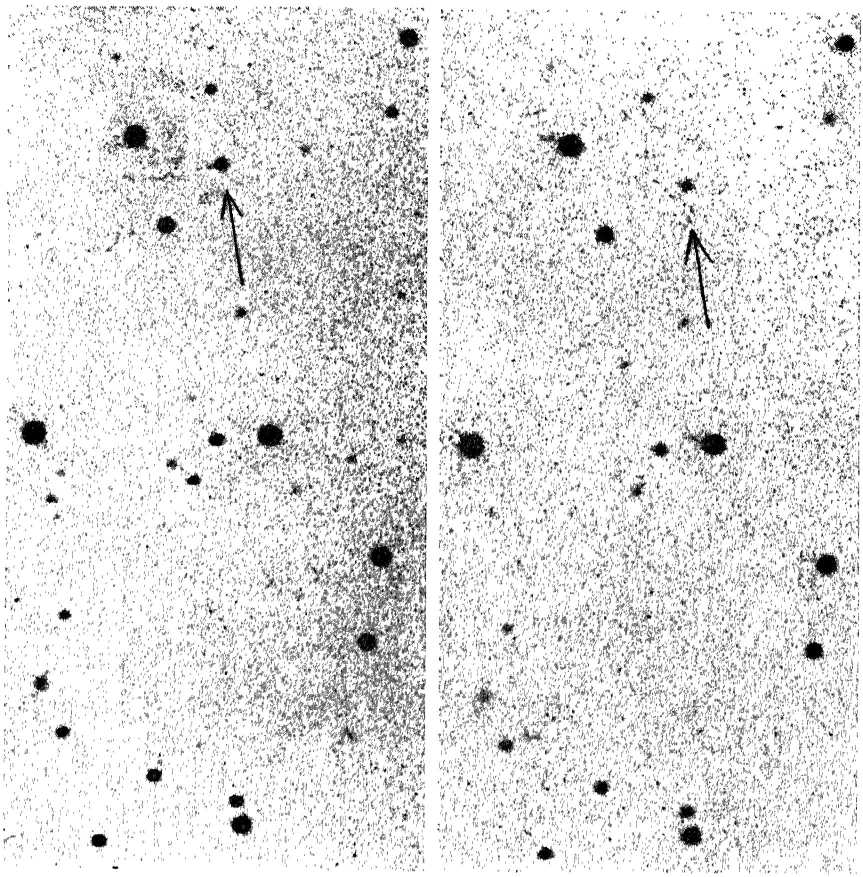
Pluto. The work of computing an accurate orbit for Neptune was slow because of the planet's long period. By 1905, Percival Lowell, among others, became convinced that there must be at least one other planet beyond Neptune to explain the orbital irregularities of Neptune and Uranus. Lowell built a large observatory at Flagstaff, Arizona, and the search was continued by the Lowell Observatory staff, even after Lowell's death in 1916. Finally, in March, 1930, the discovery of a trans-Neptunian planet was announced. Reexamination of old photographic plates later showed that Pluto had been photographed as far back as 1914. Not enough data were available at that time to distinguish it from some 15 million stars which are as bright or brighter. Accurate calculations cannot be made this soon after its discovery, but this very faint planet appears to be about the size of Mars. Apparently it has an extremely elliptical orbit, although the data are not sufficiently complete to be conclusive. It traverses its orbit in about 250 years. Its distance from the sun is about forty times that of the earth, and the intensity of sunlight is so small that even Pluto's oxygen, if any, would be frozen solid.

It is not out of the question that still other planets lie beyond Pluto, but no real evidence points to their existence.

Comets. The sun's family has many members in addition to the planets, satellites, and asteroids which we have considered so far. ***Comets*** are not visitors from interstellar realms. They are really members of our own solar system which move in long, highly elliptical orbits. In agreement with Kepler's laws, they travel very rapidly when near the sun, and very slowly when away from it, so they spend most of their time far out beyond Pluto. They return in their orbits with regularity unless badly disturbed by close approach to a planet or the sun.

Comets are usually thought of as spectacular objects streaming across the sky, with brilliant heads and long tails. Actually less

than 10 per cent of the 100,000 or more comets are visible with the naked eye. A few, like Halley's famous comet which returns every 76 years, are exceptions. The nucleus of a comet probably consists of a swarm of meteors and meteorites, but the head—which may



(*Mount Wilson Observatory.*)

Fig. 79. Pluto. Two views showing apparent motion in one day (60-in. reflector).

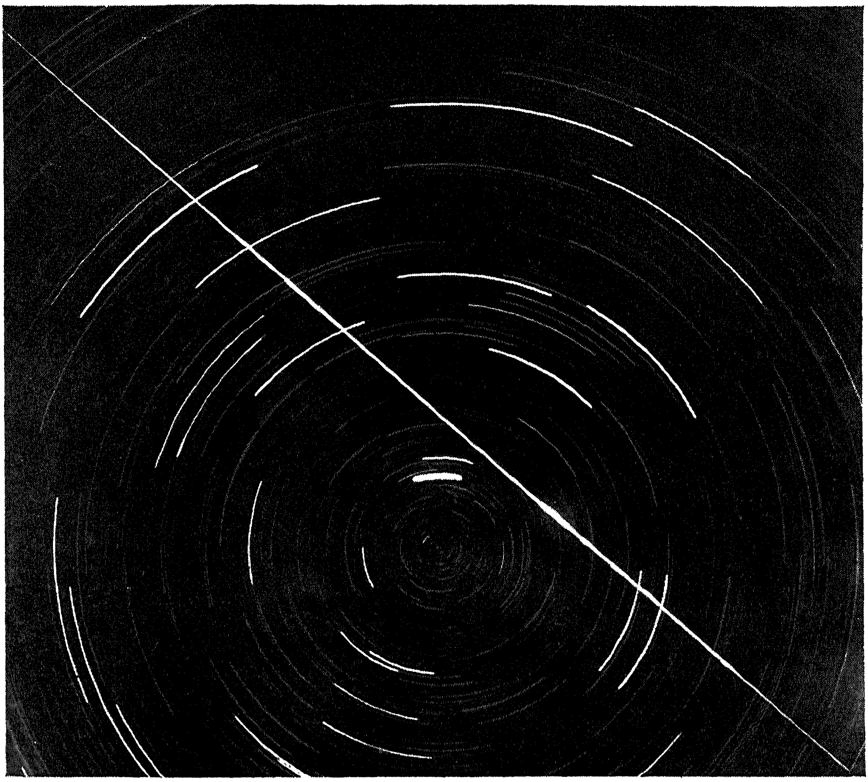
be as much as a million miles across—is composed of rarefied gas. When a comet nears the sun, the pressure exerted by the light from the sun forces gas atoms out from the comet's head, producing the effect of a streaming tail which points away from the sun. In fact, comets are frequently divided by the forces exerted by the sun. The tail is so diffuse that stars can easily be seen through it. Contrary to popular beliefs, a collision between the earth and a comet

would pass almost unnoticed because the comet's density is so low. Even a direct collision with the nucleus would hardly produce more than a brilliant meteor shower.

(*Yerkes Observatory.*)

Fig. 80.—Morehouse Comet (1908). Star "trails" were formed because the telescope was fixed on the comet which moved with respect to the stars.

Meteors. On a clear night, everyone has doubtless seen the so-called "shooting stars" which appear to flash across the sky and disappear. Of course these are not stars at all. Fortunately, most of the debris that floats about in space is very small—little larger than small pebbles—grains of cosmic dust. When these enter the earth's atmosphere, they are heated to incandescence by friction and usually are consumed long before they reach the earth. Recent estimates indicate that about 10 billion such *meteors* enter the earth's atmosphere each day.

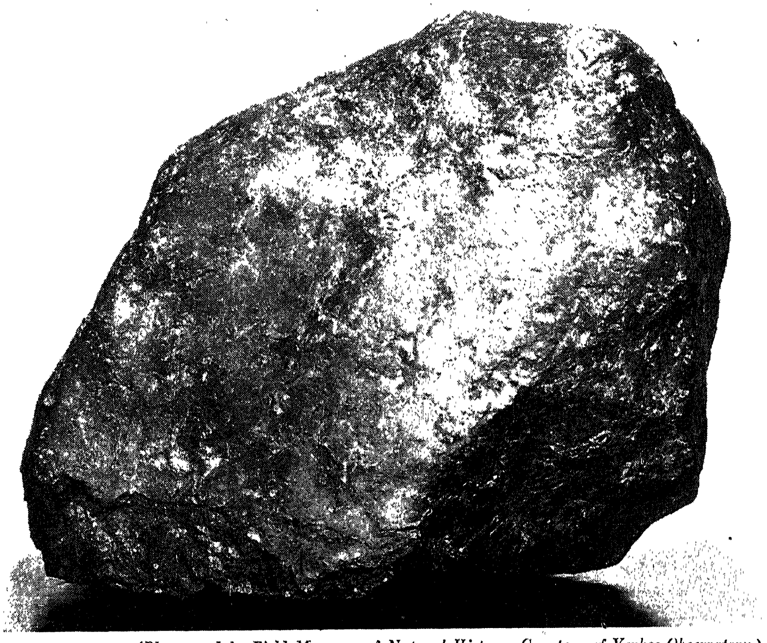


(*American Museum of Natural History.*)

Fig. 81. Meteor trail crossing circumpolar star tracks. Notice fluctuations in brightness of the trail—also that the north star is not exactly at the pole.

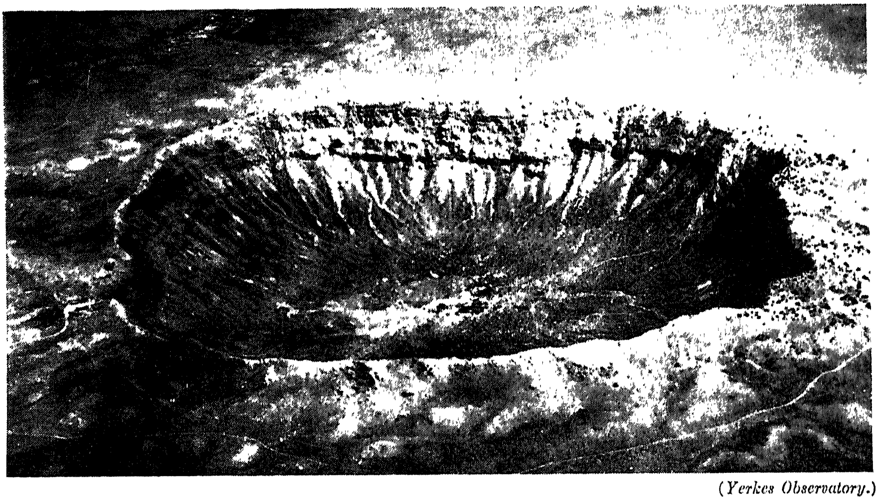
Occasionally a heavier piece reaches the earth before it is consumed or buries itself in the ground. Such pieces are called ***meteorites***. We should be thankful for the protection of our atmosphere, which only about 10 to 20 meteorites are able to penetrate each year. There is, then, little chance of a meteorite scoring a direct hit on something important on the earth's surface. However, airplanes are being designed to travel higher and higher above the earth in the near stratosphere where the chance of collision with unconsumed meteorites increases. Some authorities think that eventually this danger might become appreciable.

Meteorites tell us a great deal about the composition of other parts of the solar system. The elements found in them are the same that we know on earth. Meteorites usually may be placed in two general classes—the metallic type, rich in iron and nickel, and the



(*Photograph by Field Museum of Natural History, Courtesy of Yerkes Observatory.*)

Fig. 82. 745-lb Stone meteorite from Paragould, Arkansas.



(*Yerkes Observatory.*)

Fig. 83. Meteorite crater near Winslow, Arizona, from the air. Notice roads near the rim.

stony type, which contain mostly minerals rich in silica. There are also mixtures of the two types. Most opinion seems to be that the origin of meteorites is within our own solar system.

A spectacular monument to the whims of nature is a large meteorite crater in Arizona, 4,200 ft in diameter and 600 ft deep. The meteorite that made this crater probably fell thousands of years ago. Meteoritic masses, possibly part of the main body, have been reached by drilling beneath the south rim, and many small fragments have been found on the surface in the vicinity.

In June, 1908, a number of meteoric masses fell on an uninhabited region in central Siberia, and almost completely devastated about 1,000 square miles of territory. The probability of this happening in any given area such as New York City is of course exceedingly small.

PLANETARY STATISTICS

Planet	Mean distance from sun, AU	Orbital period, years	Eccentricity of orbit	Sidereal period of axial rotation	Satellites	Diameter at equator, miles	Mass (mass of earth = 1)	Density (density of water = 1)
Sun................	.....	......	......	25 days	....	864,000	330,000	1.4
Mercury...........	0.39	0.24	0.206	88 days	None	3,000	0.06	3.8
Venus..............	0.72	0.62	0.007	30 days (?)	None	7,600	0.82	5.2
Earth..............	1.00	1.00	0.017	23 hr 56 min	1 (Moon)	7,927	1.00	5.5
Mars..............	1.52	1.88	0.093	24.6 hr	2	4,220	0.11	4.0
Jupiter.............	5.20	11.9	0.048	9.9 hr	11	89,000	318	1.4
Saturn.............	9.5	29.5	0.056	10.3 hr	9	75,000	95	0.7
Uranus.............	19.2	84	0.047	10.8 hr (retrograde)	4	31,000	14.6	1.3
Neptune.........	30.1	165	0.009	15.8 hr	1	33,000	17	1.2
Pluto............	39.5	248	0.25(?)	(?)	(?)	4,000(?)	0.1(?)	4(?)

ASTRONOMY ADVANCES

Man's conception of the vastness of the universe has grown continually as astronomical telescopes have increased in size and improved in quality. During the last 50 years, in Europe and especially in America, private generosity and public funds have increasingly supported the building of large observatories and the carrying forward of astronomical investigation. Among the many famous observatories in this country are the Lick Observatory, California; Yerkes Observatory, Wisconsin; Harvard Observatory; Lowell Observatory, Arizona; Mount Wilson Observatory, Cali-

fornia; and the Mount Palomar Observatory, California, which will house the new 200-in. telescope.

The progress of astronomy has depended upon the cooperation of men from many institutions, with wide backgrounds in physics, chemistry, and mathematics as well as in astrophysics and astronomy. These scientists have developed new instruments and new experimental methods, formulated daring new hypotheses to be tested by experiment, and proposed new theories. Astronomical research programs must usually be planned over periods of many years, even decades. There is wide opportunity for constant interplay between experiment and theory, now that it is clearly understood that ***controlled quantitative investigation*** is the essential basis of experimental science.

Outward to the Stars. It takes more than 8 min for light from the sun, traveling at the tremendous speed of 186,000 miles a second, to reach the earth; 45 min to reach Jupiter, and 5.5 hr to reach Pluto. The ancients thought the stars were just outside Saturn's orbit, and even in fairly recent times stellar distances were badly underestimated. As we have already learned, the development of stellar parallax methods finally showed that light from the sun would need 4.3 years to reach the nearest star. The accuracy of the ***trigonometric parallax method*** has gradually been improved since its successful application to stars by Bessel and Struve and Henderson, but, as we have learned, the diameter of the earth's orbit is so small a base line that the parallax of a star 100 light-years away is only about 0.03 sec, nearly the limit of this type of measurement. Most of the many billions of stars in the universe are far more than 100 light-years distant. Other methods must be used to measure these greater distances.

Magnitude of Stars. Sirius, the "dog star," is the brightest star we can see. The other stars range down to those which are too faint even to be photographed individually. Some basis for comparison of brightness is clearly necessary. Ptolemy's *Almagest* divided the stars into six groups according to apparent brightness; in recent times, astronomers have evolved a more satisfactory scale of brightness or ***magnitude***. A first-magnitude star is 2.5 times as bright as one of second magnitude; a second-magnitude star is 2.5 times as bright as one of third magnitude, etc. With the un-

aided eye we can just see stars of about sixth magnitude, 1/100 the brightness of a first-magnitude star such as Betelgeuse. Since there are about 10 stars brighter than Betelgeuse, some by more than one magnitude, the scale has been extended past zero magni-

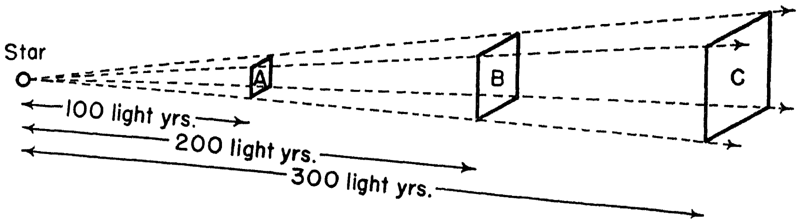


Fig. 84. The inverse square relation. Light streams at the same rate through the areas A, B, and C, but B = 4A and C = 9A (i.e., each side of C is three times each side of A; so C = 3^2A = 9A), so the light intensity or rate per unit area at B is one-fourth that at A and the intensity at C is one-ninth that at A. This illustrates the "inverse square law," that the intensity of light from a star varies inversely as the square of the distance.

tude. For example, the magnitude of Sirius is −1.6, that of the sun is −27. Telescopes with large light-gathering power permit the photographing of stars of the twentieth magnitude. Although much more accurate methods are available, it is worth noting that a skilled observer relying only on his visual sense can estimate stellar magnitudes quite well.

Observed, or ***apparent, magnitude*** depends on the distance to a star. From a physical standpoint we are interested in star types, so the intrinsic brightness or the ***absolute magnitude*** is far more important. On this scale, we correct for the fact that the intensity of light from a star decreases according to the square of the distance; that is, the same star, twice as far away, would appear only one-fourth as bright; three times away, one-ninth as bright, etc. The absolute magnitude is the apparent brightness that a star would have if placed at a standard distance of 33 light-years.[1]

On such a corrected basis, Betelgeuse has an absolute magnitude of −2.9, and Sirius 1.3. Our sun is only 4.7 but is still an average star, for the absolute magnitudes of stars are known to extend as far as 16.5.

Spectroscopic Parallax. One successful method for extending our space measuring stick was developed at the Mount Wilson Ob-

[1] Ten parsecs.

servatory by Adams and Kohlschütter. A careful study showed that the relative intensities of certain pairs of lines in the spectra of many stars depend on the ***absolute magnitudes*** of the stars. Thus if we can measure the intensity ratio of some of its spectral lines,

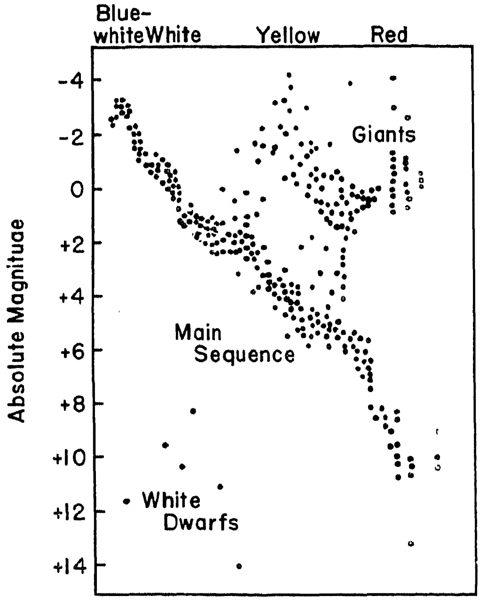


Fig. 85. "Russell diagram." This indicates some connection between absolute magnitude and "color" of stars.

we immediately know a star's absolute magnitude without measuring its distance. Of course, its apparent magnitude can also be measured. Since the latter quantity depends on the distance as well as on the absolute magnitude, we are not surprised to learn that a simple equation gives the distance to a star in terms of its apparent magnitude and its absolute magnitude.[1] Thus, the spectrum of a star yields a quantity, the absolute magnitude, which can be used in this equation to determine the distance to the star. This new means of measuring stellar distances was worked out originally for the close stars so that it could be checked by results of direct trigonometric measurement. This new method can now be applied to any star that gives a good spectrum; therefore

[1] This equation is: $5 \log p = M - m - 5$, where p is the parallax, M is the absolute magnitude, and m is the apparent magnitude.

it vastly extends the depth of the universe to which man can penetrate.

Variable Stars. It has been known since the time of the ancients that some stars vary markedly in intensity. Modern observations show that these variable stars actually fall into several classes.

Novae. Occasionally a comparatively weak star suddenly flares up and becomes tremendously bright, sometimes increasing to 100,000 times the absolute brightness of the sun within a few days, and afterwards, over a period of 10 to 20 years, decreases nearly to its original intensity. Such a star is called a *nova.* The nova that inspired Tycho Brahe in 1572 was probably the most brilliant ever recorded. What actually happens in such a terrific stellar explosion remains a challenge to the minds of astronomers.

Long-period Variables. Stars that vary periodically in intensity over cycles of from several months to several years are called *long-period variables.* Most of the 8,000 or more known variable stars are of this type, although some have irregular periods. The cause of these cyclic pulsations presents another of the astronomical problems that are still being investigated. The first star of this type was discovered by an Italian amateur astronomer in 1596. Today a group of amateur astronomers, known as the American Association of Variable Star Observers, is performing a useful service in discovering and studying variable stars.

Double Stars. A large number of variable stars change in appearance simply because they are double stars, that is, two stars revolving about a common center, often with periods of a few days. When one comes between us and the other, the light intensity will be reduced. These are called *eclipsing* variables. Observations of the variation in light intensity often permit accurate estimates of the relative sizes and the orbits of the two stars. One of the best known double stars is our brightest—Sirius. Its companion is of a strange type known as a *white dwarf,* hotter than our sun and 60,000 times as dense as water!

Cepheid Variables—A New Measuring Stick. A method of determining distances even greater than can be measured by any means so far discussed makes use of *cepheid variables,* a type of variable star which fluctuates quickly and regularly in intensity. Miss Leavitt at Harvard first pointed out in 1908 that the periods

of all cepheid variables depend on their absolute magnitudes—the shorter the period the brighter they are. The relation between absolute magnitude and period was worked out by Shapley, using close stars the distances of which had already been measured by

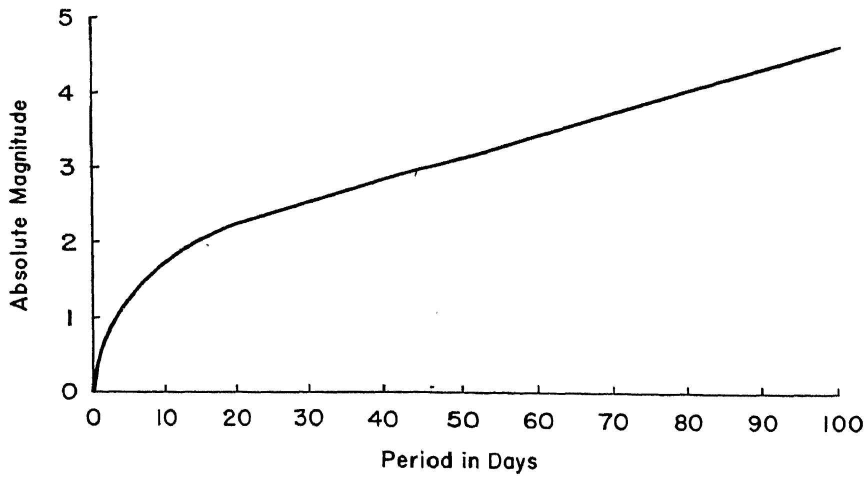
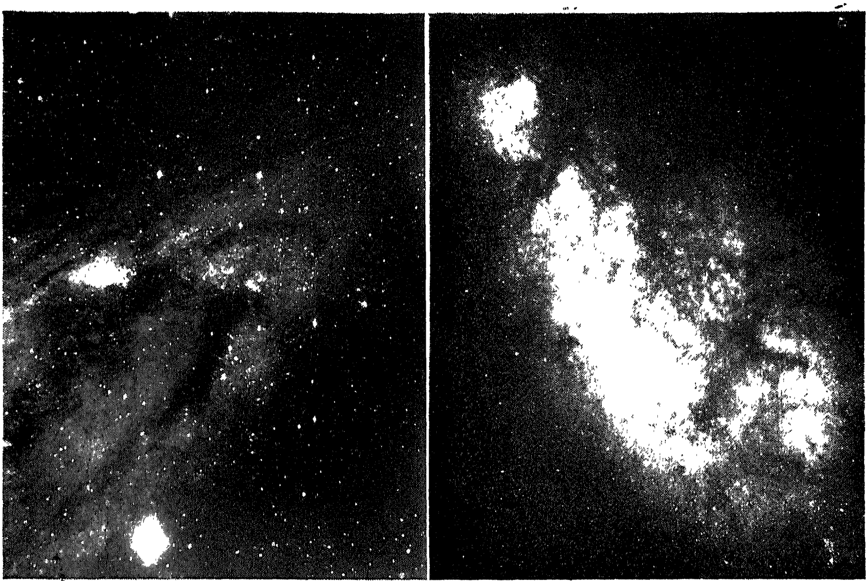


Fig. 86. Shapley's relation between period and absolute magnitude for cepheid variable stars.

the trigonometric or spectroscopic methods, so that again earlier measurements were used for purposes of calibration.

Whenever a cepheid variable is found anywhere in the universe and its period determined, its absolute magnitude is known at once from Shapley's relation (Fig. 86). If the apparent magnitude is then measured, the parallax or distance can be determined easily from the equation mentioned in the discussion of spectroscopic parallax (page 118). Distances of more than 100 million light-years have been measured by this method, extending the known depth of the universe to a million times that determined through trigonometric parallax measurements. Thus if cepheid variable stars are present and if our telescopes have enough light-gathering power to "see" them, a measurement of distance can be made. No wonder astronomers want larger and larger telescopes to push farther into space.

Such measurements as we have just considered, combined with spectroscopic and thermocouple methods which tell us much about the motion and temperature of stars, give us increasing ability to survey the universe and to see how it is arranged.



(*Mount Wilson Observatory.*)

Fig. 87. Comparison of star clouds of Milky Way (right) with portion of Andromeda Nebula (60- and 100-in. reflectors).

OUR GALAXY

On a clear, moonless night, the Milky Way stands out as a beautiful, hazy band of light across the sky, but upon examination by a powerful telescope it is seen to be made up of a countless number of stars. Were it not for the earth below us we should see it as a continuous circle around the sky. Herschel was the first to make star-density counts, and more recent extensions of his work show that the density of visible stars is at least several thousand times as great in the Milky Way as off to the side. Measurements of stellar distances show that our sun is about two-thirds of the way from the center of a vast system of stars which is shaped much like a flat watch. As we look out along the plane of the system we therefore get the effect of the great star belt of the Milky Way. This huge system, which we call our ***galaxy,*** is variously estimated at from 50,000 to 200,000 light-years in diameter, and about one-tenth as thick. Only about 5,000 stars can be seen with the unaided eye, but it has been estimated that of 30 to 100 billion stars in our galaxy, perhaps 4 billion could be photographed by the present 100-in. Mount Wilson reflector. Yet, with all this enormous num-

ber of stars, the average distance between them is so large (perhaps 10 light-years) that space is almost empty.

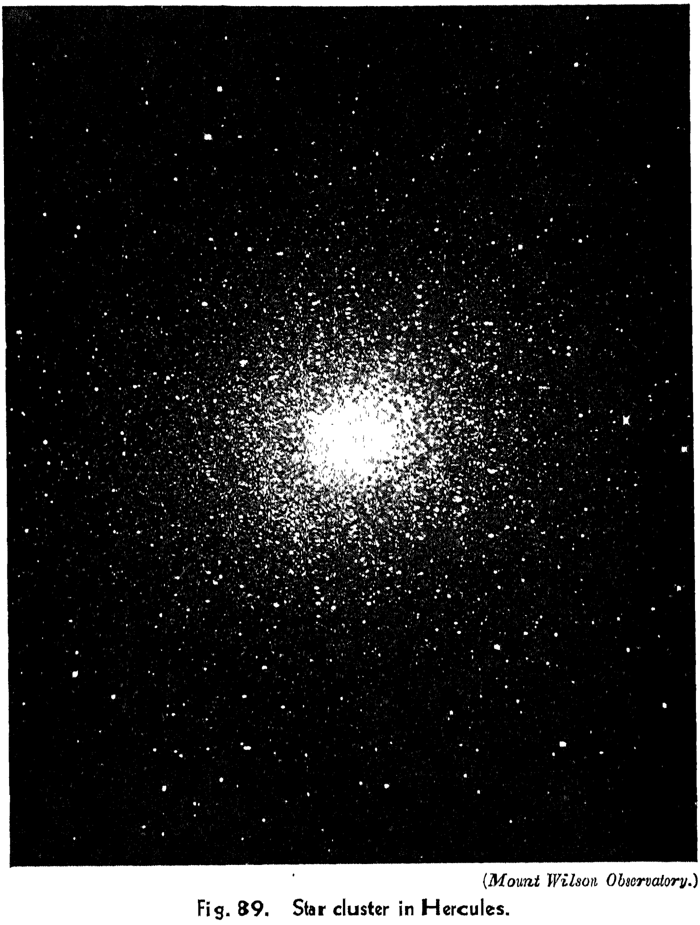
Many subgroupings of stars, called ***clusters,*** exist within our galaxy. One of the most famous is known as the Cluster of Hercules,

(*Mount Wilson Observatory.*)

Fig. 88. A spiral nebula on edge. Our galaxy is probably of similar form (60-in. reflector).

33,000 light-years away in the constellation of Hercules. Although barely visible with the unaided eye, the telescope shows that it is a myriad of stars grouped together in a globular cluster. Each star is probably many hundreds of times as bright as our sun, and some estimates indicate that 100,000 stars may be included. Such clusters as a unit are fairly stable, with a considerable amount of motion of the individual stars with respect to one another. There

is very little chance for a collision between the stars, for the cluster is still almost entirely open space. There is room enough so that each star might easily have its own planetary system. At least 100 of these globular clusters are known to exist, most of them near the boundaries of our galaxy.

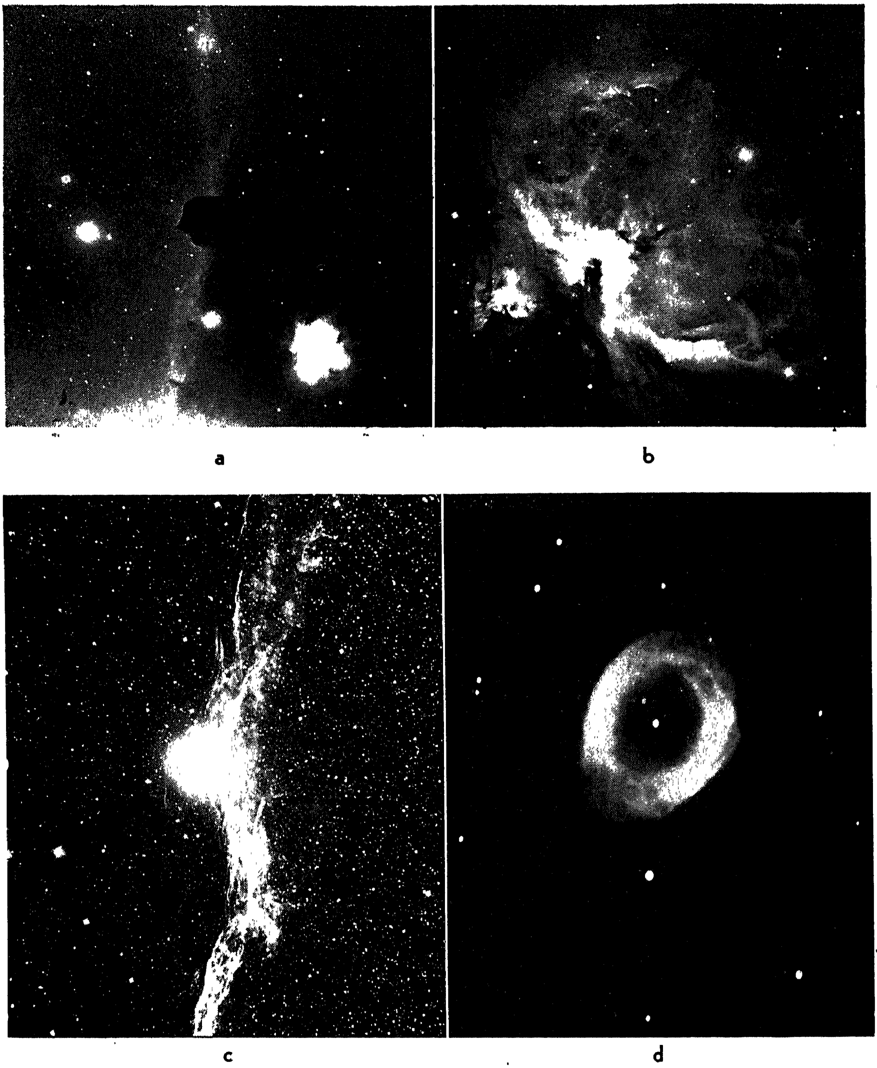


(*Mount Wilson Observatory.*)

Fig. 89. Star cluster in Hercules.

Also within our star system are great quantities of cosmic dust —some of it collected in dark clouds that obscure light from stars behind, some of it in clouds that are luminous because of near-by hot stars. These clouds are often called *diffuse* or ***gaseous nebulae.***

Our galaxy seems to be not completely stable, for our solar system is moving about 12 miles per second with reference to the nearest star, and considerable motions relative to each other



(*Mount Wilson Observatory.*)

Fig. 90. Diffuse nebulae (100-in. reflector). (a) Dark bay in Orion nebula; (b) nebula in Orion; (c) filamentary nebula in Cygnus; (d) ring nebula in Lyra.

(called "proper motions") are observed for nearly all close stars. The large collection of photographic plates taken by Rutherfurd in the 1860's (page 79) has provided some of the oldest records for comparisons of star positions then and now in order to determine proper motions, especially of the Pleiades. Many programs of star observation have been in operation for more than 40 years.

Recent work indicates that our whole galactic system rotates about its center of mass, which is probably what keeps the various units from being drawn to the center by mutual gravitational forces. The sun's period of revolution about the center of the

(*Yerkes Observatory.*)

Fig. 91. The great spiral nebula of Andromeda.

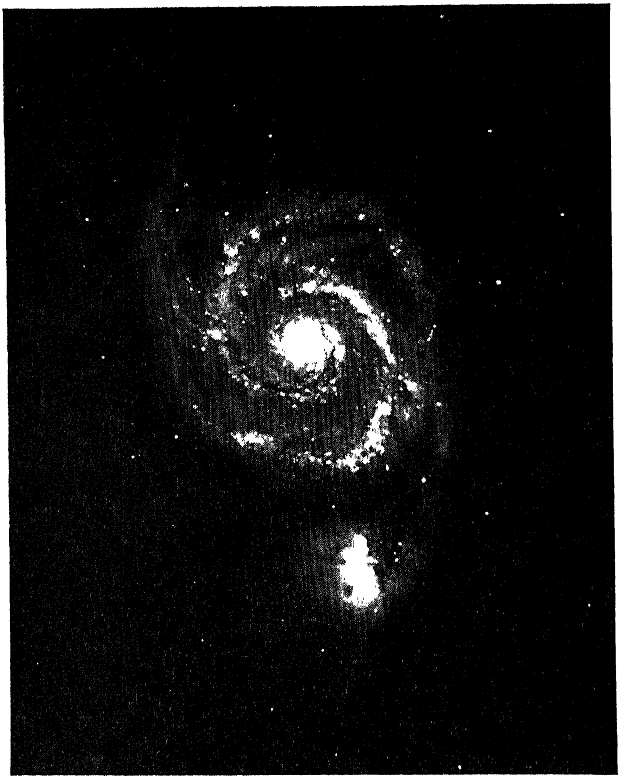
galaxy appears to be about 200 million years, and it, along with our earth, travels at about 200 miles per second in this enormous orbit!

OUR GROWING UNIVERSE

Present-day instruments enable us to look far beyond the edge of our own galaxy. Near the edge we find the Magellanic Clouds—hazy, diffuse star groups. As we go out still farther, we see many spiral-shaped clouds of light which Sir William Herschel called "island universes." At first it was thought that these were gaseous, but within the last 15 years new telescopes have shown that these

great spirals are composed of individual stars, as is our own galaxy. Cepheid variable stars in them tell us their distances, and the nearest is 700,000 light-years away!

These distant nebulae often have the form of large double-



(*Mount Wilson Observatory.*)

Fig. 92. "Whirlpool" spiral nebula in Canes Venatici (100-in. reflector).

armed spirals. While our own galaxy does seem to be appreciably larger than most of the other galaxies yet discovered, this may be only a result of our limited powers of observation. Various classifications of galaxies have been made as to shape, size, and distance; some astronomers have suggested that perhaps certain smaller ones are really units in a supergalaxy.

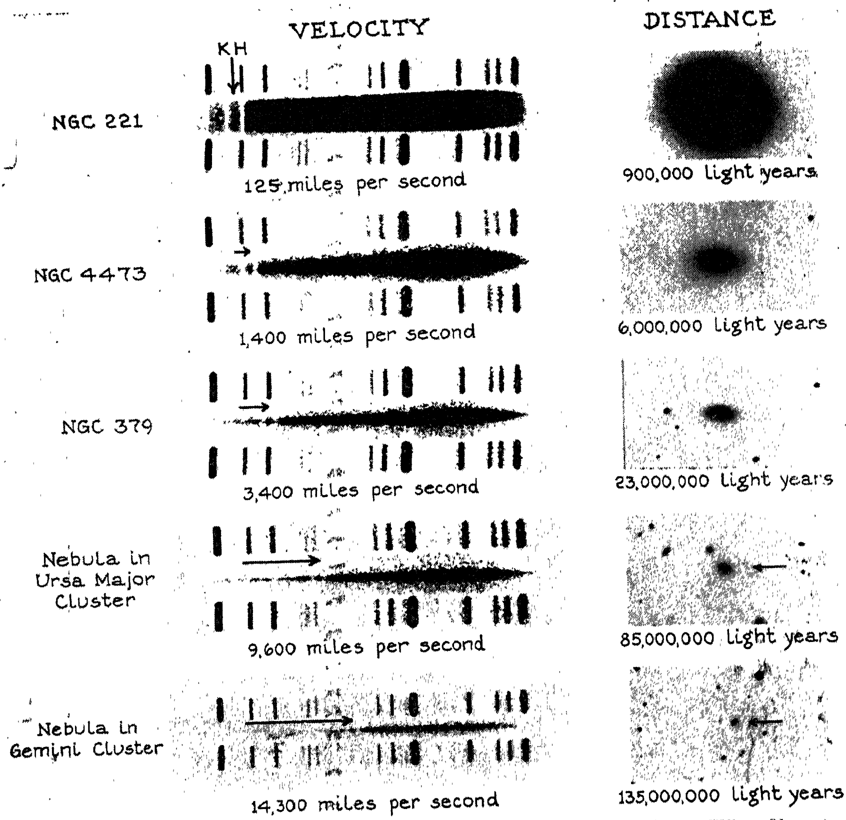
In the hands of men such as Hubble and Humason at Mount Wilson, the spectroscope has yielded a great deal of information about these distant galaxies. Even though the light from them is

extremely weak, the new instruments and long-continued exposures with modern sensitive plates permit the building up of good images. Atoms in these galaxies seem to behave as they do here on earth, and the distant stars are similar to our near-by stars.

(*Mount Wilson Observatory.*)

Fig. 93. Close group of spiral nebulae in Pegasus (60-in. reflector).

Receding Nebulae. One of the most interesting questions raised by the work of Hubble is that of the apparent velocities of these distant nebulae. As we learned earlier, comparison of the difference between the apparent wave length of the light emitted by a given element here and on a distant nebula provides, according to Doppler's principle, a method for estimating the direction of motion and speed of the nebula. Near-by nebulae show "shifts" sometimes toward the blue and sometimes toward the red end of the spectrum. In other words, some are approaching us, others receding from us. But when the more distant nebulae are photographed they all show a red shift—all are receding from us. Still more startling, the farther away from us the nebulae are, the faster they recede. The nebula in Gemini, 130 million light-years distant, is apparently flying away from us at the tremendous rate of 14,000 miles per second!



(*Mount Wilson Observatory.*)

Fig. 94. Doppler shifts of nebulae at various distances. The shifts toward the red end of the spectrum increase as distance increases. This indicates that the more distant nebulae are speeding away from us faster than the closer ones.

Are these velocities real? Is the universe really exploding at this terrific rate? Is there something fundamentally wrong with our logic or is some new phenomenon coming into play at these great distances? It is interesting to note, as Hubble points out, that recent estimates of the speed at which the outermost nebulae are now receding indicate that if their course were traced back to the time our sun was formed (about 3 billion years ago according to the best estimates) all the universe was then concentrated in a small region in space. Apparently, expansion of the entire universe started at that time. This hypothesis involves serious questions as to the nature of matter and energy which we are not yet prepared to answer.

The stellar distances are so great in terms of light-years that measurements we make now compare stars as they existed at very different periods in the history of the universe. When we photograph the sun, we see the sun as it was 8.3 min before, while when we look at the distant nebulae, we see them *not* as they are now but as they were 100 million or more years ago. Observations on phenomena of this type, where distances are large as compared to the distance traveled by light in an appreciable time, clearly can be considered only on the basis of the theory of relativity which takes into account both distance and time.

A discussion of relativity is beyond the scope of this book, although we shall use many of the concepts as we go along. In general, the relativistic considerations of Einstein, de Sitter, Le Maitre, Eddington, Jeans, Tolman, and numerous others have led to several speculative cosmogonies with interesting properties. According to these theories of the origin and structure of the universe, matter and space are probably not independent, and it is possible that the universe may be closed and finite rather than infinite. These theories, however, have not yet provided a complete interpretation of the apparently expanding universe. Some theories have even suggested that the universe may pulsate, or alternately expand and contract.

A Star-gazing Session. We might wish to become acquainted personally with a number of the more colorful stars, several with Jekyll and Hyde or even multiple personalities. And perhaps we care to meet a few nebulae, some of them diffuse and some of them distant galaxies. The most impressive constellations of the northern hemisphere are overhead on a January evening, but to avoid the coldest weather, let us take a midnight stroll away from city lights on a clear, moonless November night. Figure 95 is a chart of the sky as it appears at midnight about the middle of November at the latitude of New York City. To understand how star positions would be changed at another date, it is only necessary to recall that the sidereal day is 4 min shorter than the solar day, so a star crosses the meridian 4 min earlier tomorrow than it does today, or about two hours earlier a month from today (see page 82).

On this night, we see the Milky Way extending directly overhead from northwest to southeast. This band of light, which

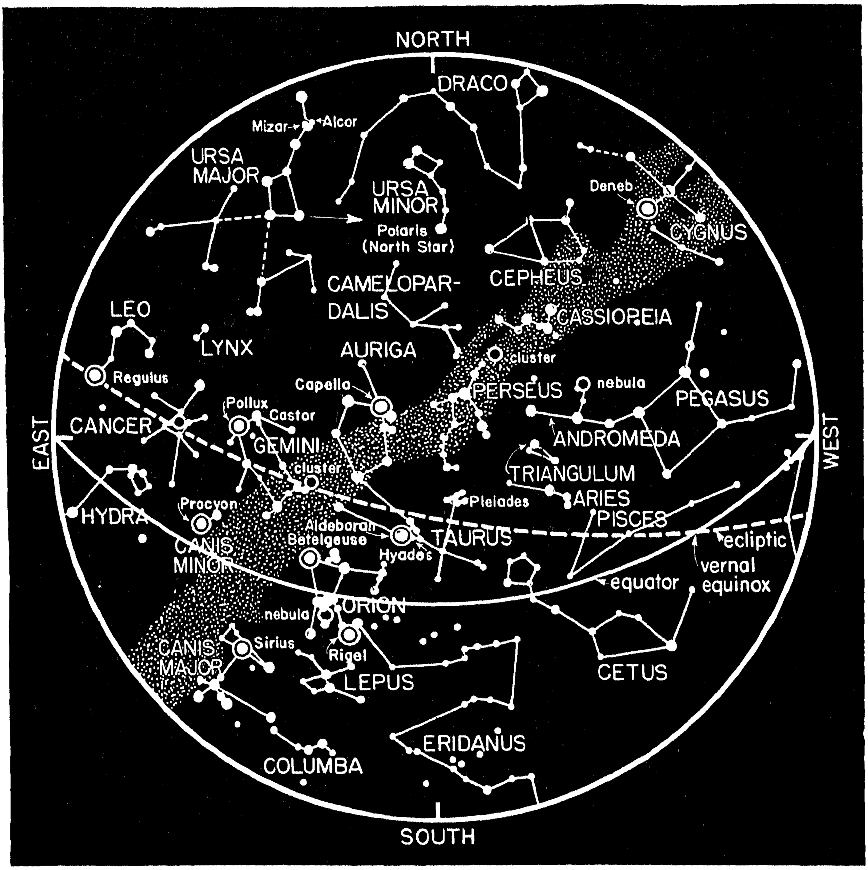
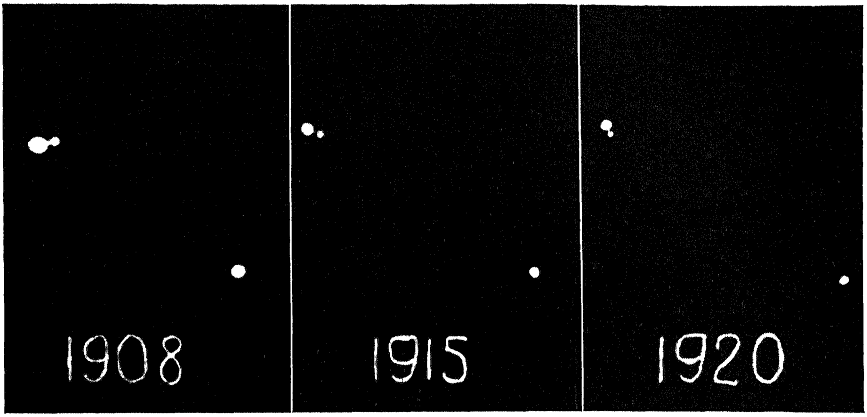


Fig. 95. Star chart for midnight Nov. 20 at latitude of New York. The Milky Way extends overhead from northwest to southeast. (Imagine yourself lying on your back with your head toward the north—the chart held above you shows star positions as they appear in the sky.)

actually comes from the countless stars of our galaxy, will serve as a good reference line to help us locate some of the more prominent star groups, or ***constellations***. Where the Milky Way dips into the northwest horizon stands the greater part of the Northern Cross, otherwise known as Cygnus, the "swan." This setting constellation dominated the sky early in the evening. It was the parallax of one of the fainter stars in Cygnus that Bessel measured more than a century ago.

Following the Milky Way, we see, about halfway to the zenith, a "W" of bright stars known as Cassiopeia, the "lady in the chair." What now is a very ordinary star in Cassiopeia was once a nova, so



(*Yerkes Observatory.*)

Fig. 96. Photographs of the double star "Krueger 60" showing orbital motion.

brilliant that it was visible even by day. This was the nova that stimulated Tycho Brahe's interest in astronomy.

Almost halfway between the northern horizon and the zenith we find Polaris, the pole star, well isolated from other bright stars. Just above the northeast horizon, standing on its handle, is the Big Dipper. Most of us know that the two stars which form the drinking end of its cup point toward Polaris. The ancients, instead of seeing a dipper, made a huge bear out of the stars in this part of the sky; hence the name Ursa Major for the constellation of which the Big Dipper is a part. The second star from the end of the dipper's handle, Mizar, has a faint companion, Alcor, which is said to have been used in old times as a test for acceptable eyesight. The telescope shows that Mizar itself is a double star. In fact, it was separated in the seventeenth century, the first telescopic double to be discovered. Moreover, spectroscopic observation has led to the conclusion that Alcor and both parts of Mizar are three pairs of "waltzing" twins, each too intimate to be separated by the telescope.

West of Polaris, and between Cygnus and Cassiopeia, is the faint constellation Cepheus. Cepheid variables (page 119) borrowed their name from this constellation because many such stars appear in this part of the sky. Polaris, itself variable in intensity, is supposed by some to be of the cepheid type.

Above the western horizon is the "great square" of the constellation Pegasus. The chain of stars extending from this square

toward the zenith is Andromeda, the "chained lady." Extending toward Cassiopeia from the central bright star of Andromeda are, in succession, two faint stars and a diffuse patch of light. A small telescope shows this spot to be elongated, but only on a photograph taken with a large telescope does there appear the real structure of the Great Spiral Nebula of Andromeda (Fig. 91). This nebula, unlike diffuse nebulae, actually is an immense system of stars like the galaxy to which we belong. Although this nebula, perhaps ten to twenty times farther away than the edge of our galaxy, is the most distant group of stars usually visible to the naked eye, it is one of the nearer of our neighboring galaxies.

Immediately south of the zenith is a group of faint stars, the Pleiades. Arguments as to whether it contains six, seven, or eight stars cease when a telescope reveals hundreds of them. Many of the stars in this group are surrounded by diffuse nebulous material which can be seen by the light it scatters. The Pleiades is a true family of stars, an *open cluster*. Although it is a member of our galactic system, it moves more or less as a unit with respect to the center of the galaxy. This cluster and the stars just to the south and east of it make up the constellation Taurus, the "bull." The V-shaped group of stars including reddish Aldebaran, the brightest star in Taurus, is, like the Pleiades, an open cluster belonging to our galaxy.

To the southeast of Taurus is one of the most attractive constellations, Orion, the boastful hunter who figured in ancient legends. A distinguishing feature of this group is Orion's belt, a line of three almost equally spaced bright stars. Similar in length, but much fainter, is the dagger hanging near the lower end of the belt. Those with keen eyesight can detect something peculiar about three faint points of light forming the lower part of the dagger: the tip barely resolves into two parts, and the central spot has a hazy appearance. A telescope shows that each of these three spots is really a group of stars. Moreover, the middle group is imbedded in a general luminosity. The glowing matter in this region is the Great Nebula in Orion (Fig. 90b). It is rarefied gaseous material which apparently shines from the light of stars near it. On photographs from a telescope, there appear dark "clouds" of obscuring matter which seem to overhang parts of the luminous region. The bright and dark material may be similar in character but differently located with respect to bright stars. Like other diffuse

nebulae, that in Orion is a part of our galactic system. It is a mere thousand light-years distant.

The two brightest stars in Orion are on opposite sides of the belt and about the same distance from it. The one that almost touches the Milky Way, Betelgeuse, Orion's armpit, has an orange-red hue, and the other, known as Rigel, one of Orion's feet, has a bluish tinge. The diameter of Betelgeuse was estimated at Mount Wilson by means of the ***stellar interferometer*** devised by Michelson. This star turned out to be a giant, with a diameter several hundred times that of the sun. Another interesting characteristic of Betelgeuse is that its intensity fluctuates appreciably, but over irregular intervals of time.

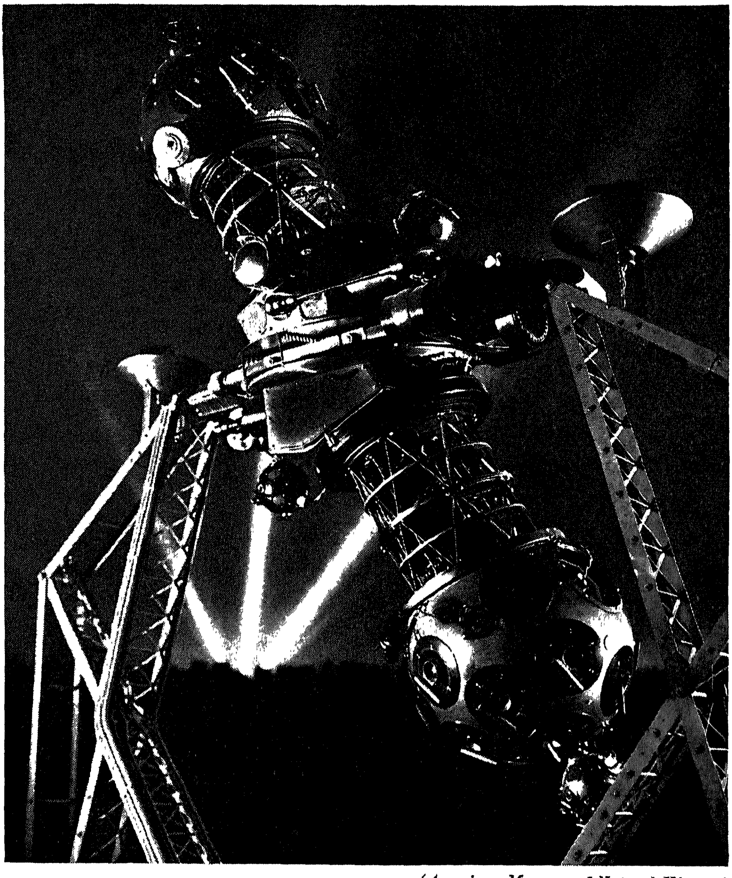
Trailing Orion, but on the same side of the Milky Way, is the "big dog," Canis Major. Dominating this constellation is blue-white Sirius, which we know to be the brightest star in the sky. On the other side of the Milky Way and forming an equilateral triangle with Sirius and Betelgeuse is another bright star, Procyon. Its constellation is Orion's "little dog," Canis Minor. Procyon and Sirius are double stars whose faint companions are very dense. Sirius' companion is only a few times the diameter of the earth but has a mass about one-half million times as great. Procyon's even tinier partner is 200 times more dense than that!

If we climb the Milky Way, we see above Procyon the stars Pollux and Castor, the "twins" of the constellation Gemini. Sharp eyes can detect faint spots of light on the Milky Way in the neighborhood of Auriga and Gemini. A large telescope shows that these are clusters of astonishing numbers of stars. Again, they are subgroups in our galaxy, although most clusters of this type (globular clusters, see page 122) cling to its boundaries.

Just rising, directly to the east, is another bright star, Regulus. Although white to the naked eye, Regulus is a telescopic double of which the fainter member is purple. The entire range of colors may be found in the stars. There are even some stars which give off only infrared light, completely invisible but detectable by means of delicate instruments.

The section of the sky about Orion has more than its share of bright stars; Sirius, Capella, Rigel, and Procyon are, in order, four of the eight brightest stars. Betelgeuse and Aldebaran are about first magnitude, and Pollux, Regulus, and Castor rank not far behind. [We realize that the order would be different in terms of

absolute magnitude, because, for example, Sirius and Procyon are relatively close to us, 9 and 11 light-years, respectively, while Betelgeuse is about 270 light-years away and Rigel, at 540 light-years, is one of the more distant of the bright stars. (See page 117).]



(American Muesum of Natural History.)

Fig. 97. Projector in the Hayden Planetarium. Five planetariums in American cities acquaint millions with celestial phenomena.

It would be easy to extend our session of star gazing—to investigate less apparent groups of stars, to seek out the roaming planets which lack the stars' "twinkle," or to wait for the constellations that will rise in another hour. By this time, however, we have seen enough to wonder at similar occasions in the past when we have noticed above us nothing more than a few thousand stars.

MAN AND THE UNIVERSE

The simple wonder of early man about the cause of day and night has led further and further, but it is certain that we are only beginning to understand the universe.

The volume of the part of the universe which has been studied increased about a billion times within the last few decades. New tools and new methods wait to be developed and used in the future, and many new galaxies wait to be discovered. Nevertheless, if the universe is limited, perhaps man can eventually penetrate to its boundaries.

Experiment and Theory. Our glimpse of the gradual development of astronomical knowledge from its beginnings is not intended to be complete, but it is hoped that it conveys the idea of how a science lives and develops, and what we mean by science.

We have seen that the increasing use of the experimental method is probably the most important factor in the growth of modern science. The spirit of "controlled quantitative investigation," which Galileo so ably demonstrated, has become the basis of the present-day approach to problems in all fields of science, and it is being applied more and more in other areas of human activity.

The possibilities for such experimentation naturally differ considerably in the various fields. In the physical sciences it is usually much easier than in other fields to separate carefully the important factors in a phenomenon, and to measure accurately what happens to the other quantities when one factor is varied in a controlled fashion. Galileo was able to isolate and measure such quantities as mass, distance, and time when he studied the speeds and acceleration of falling bodies, and so he discovered the relationships between these quantities. Similarly, the elements in the outer parts of the sun were identified by comparing the Fraunhofer lines in the sun's spectrum with spectra of elements observed in the laboratory. Although the astronomer may make many types of controlled investigations, he has some restrictions because his laboratory is on so vast a scale that he cannot, for example, vary conditions in the interior of a star to see what would be its influence.

The complexity of living organisms makes complete knowledge and control of all the factors very difficult for the biologist, but even

so he has already progressed far. The future will surely bring great advances in the life sciences through this method.

In the fields of social science, the much greater complications introduced by the nature of the human organism itself, and the further complications caused by the interaction between individuals and the factors operating in social systems, make controlled quantitative investigations much more difficult than in the natural sciences. Only a beginning has been made thus far, but in time scientific methods will almost certainly be adapted and applied to the social fields.

In many instances, we have seen how important to the growth of science is the constant interplay between theory and experiment. Out of facts and knowledge great generalizations and theories grow when the genius of some man or a group of men is able to recognize simple fundamental principles that underlie related phenomena in nature. The great value of a theory, even an imperfect one, as a basis for interpreting experimental results, for predicting new phenomena, and for suggesting further experiments, has been demonstrated time after time. We have seen how the planet Neptune was discovered because observations of the path of the planet Uranus did not agree with the Newtonian theory of planetary motion. Either the theory was wrong or the existence of a new planet had to be postulated to explain the deviations. As we saw, the position of the unknown planet, calculated to give agreement between observation and theory, led to the discovery of Neptune in almost exactly the predicted position.

Likewise, through the give and take between a growing theory and experiments, hypotheses may be tested and abandoned if incorrect, while proven hypotheses are used to modify or extend the theory to give a more and more satisfactory description of phenomena. The success of the objective scientific method has been truly remarkable, and yet with it has come the humble realization that we have only scratched the surface in the attempt to understand nature.

Where does man come into the scheme of the universe? The vastness of the cosmos is such that if the known part were reduced to the size of the United States the earth could just barely be observed with the most powerful of microscopes. As for man, his works would be completely unobservable. Yet it is quite certain that in this whole universe comparatively few spots exist with the

same favorable conditions for life as on the earth, and it is entirely possible that intelligent life has evolved only on this tiny planet. In the course of a few thousand years out of the long ages of time, the human mind has enabled man to explore the universe and to control his immediate surroundings with remarkable success. Now let us go ahead to discover what man has learned about this world, particularly about the nature of matter, energy, and radiation.

FOR STUDY AND READING

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SUMMARY

Important in astronomical telescopes are ***light-gathering power, magnification,*** and ***resolving power.*** Mirrors have no chromatic aberration and are easier than lenses to make in large sizes. The largest refractor is 40 in. in diameter (Yerkes), and the largest reflector is 200 in. (Mount Palomar). With the equatorial mounting for astronomical telescopes, an astronomical body may be located from its ***declination*** and ***right ascension*** and the sidereal time. Telescopic images are usually photographed. ***Sidereal time*** is used in astronomical measurements, and ***mean solar time*** is used for civil purposes. Distances to near stars can be obtained by triangulation with the diameter of the earth's orbit as a base line. The nearest star has a ***parallax*** of 0.76 second of arc, corresponding to a distance of 26×10^{12} miles or 4.3 ***light-years.***

The ***spectrograph*** gives the composition of the outer parts of astronomical bodies, and stellar velocities.

The sun, a fairly typical star, is 93 million miles distant and 864,000 miles in diameter. The ***photosphere*** (6000°C) is the visible

part and contains the ***sunspots***. Outside this are ***reversing layer, chromosphere,*** and ***corona.*** The tremendous power radiated from the sun is at the expense of a gradual reduction of mass.

Planetary data are summarized in the table on page 115. Some peculiarities of planets are: ***Mercury*** has no atmosphere, the same side always faces the sun, and, like Venus, it exhibits phases; ***Venus*** is clouded and has little oxygen or water but much carbon dioxide; ***Mars*** shows "canal" markings and polar ice caps and may have some form of life; ***Jupiter*** and ***Saturn*** have methane and ammonia atmospheres; Saturn has "rings" about it and was the most distant planet known to the ancients; ***Uranus,*** discovered in 1781 by Herschel, is the only planet with axial rotation from east to west; ***Neptune*** was predicted by Leverrier and discovered by Galle in 1846; and ***Pluto*** was discovered at the Lowell Observatory after having been predicted from irregularities in Neptune's orbit. Our moon has a diameter of 2,163 miles, is about 240,000 miles from the earth, and has a total period about the earth of 29½ days. It has a cratered surface, holds no atmosphere, and the same side always faces the earth. The moon exhibits phases and produces tides and solar eclipses. Other members of the solar system are the ***asteroids*** (1,400 are catalogued, the largest being 500 miles across) chiefly between the orbits of Mars and Jupiter, and ***comets*** in very elongated orbits. ***Meteorites*** give clues to the composition of matter in the solar system.

From a star's ***magnitude*** or apparent brightness and its ***absolute magnitude,*** which may be measured spectroscopically, its distance may be calculated. Another method, which gives distances to star groups as distant as 100 million light-years, involves a relation between absolute magnitude and period of intensity change of ***cepheid*** variable stars. Other types of variable stars are ***novae, long-period variables*** and ***eclipsing double stars.***

The Milky Way is a single ***galaxy*** which includes our sun. It is about 100,000 light-years in diameter and contains 30 to 100 billion stars (estimated). Numerous ***star clusters*** and ***diffuse nebulae*** exist within this galaxy. There are other galaxies, including ***spiral nebulae,*** far outside of ours. Spectroscopic measurements indicate that all distant galaxies are rapidly receding from us, as though the universe were expanding.

Dimensionally negligible man has fathomed the universe, largely through ***controlled quantitative investigation.***

QUESTIONS

1. Why are telescopes used for astronomical observation?
2. How does the light-gathering power of the 100-in. Mount Wilson reflector compare with that of the human eye?
3. What is the magnification of a telescope in which the objective lens has a focal length of 10 ft and the eyepiece a focal length of 1 in.?
4. Why are the new large telescopes reflectors rather than refractors?
5. How are positions of celestial bodies specified? To what terrestrial coordinates do the commonly used astronomical coordinates correspond?
6. Why is the equatorial mounting used almost exclusively for large astronomical telescopes?
7. How would you classify the mountings of the telescopes shown in Figs. 42, 44, 50, 53, and 55?
8. What is the declination of the celestial north pole? Its right ascension?
9. How is time involved in astronomical observations? What kind of time do astronomers use? How is it determined?
10. How long was the exposure of Fig. 81?
11. How can triangulation methods be used to measure the distance to a star?
12. What is the relation between the distance to a star and the star's parallax?
13. What is a light-year? What astronomical quantities are expressed in terms of light-years?
14. Of what use is the spectroscope to the astronomer?
15. How does the spectroscope make possible the estimation of stellar velocities? What is the "red shift"?
16. What are sunspots? In what part of the sun do they appear?
17. How have elements in the various outer regions of the sun been identified?
18. Why is there an uncertainty in the period of axial rotation of Venus?
19. What is peculiar about Saturn? Jupiter? Uranus?
20. Why can Venus never be seen at midnight? Does any other planet behave this way?
21. On what basis was the existence of Neptune predicted?
22. In what phase (or phases) of the moon can a lunar eclipse occur? A solar eclipse? The highest tides?
23. What are the methods of estimating distances to the farther stars? How great are these distances? How extensive is our galaxy?
24. In Fig. 79 are there any images other than of Pluto which seem not to belong to ordinary stars? What about Fig. 91?
25. Does the growth of astronomy imply anything more than an ever-increasing accumulation of facts?
26. How does the brief survey of one science help us understand what we mean by *science?*
27. What is a controlled quantitative experiment? What is its role in science?
28. Why must an accepted theory rest fundamentally on experimental results? How do experiment and theory go hand in hand in scientific work?

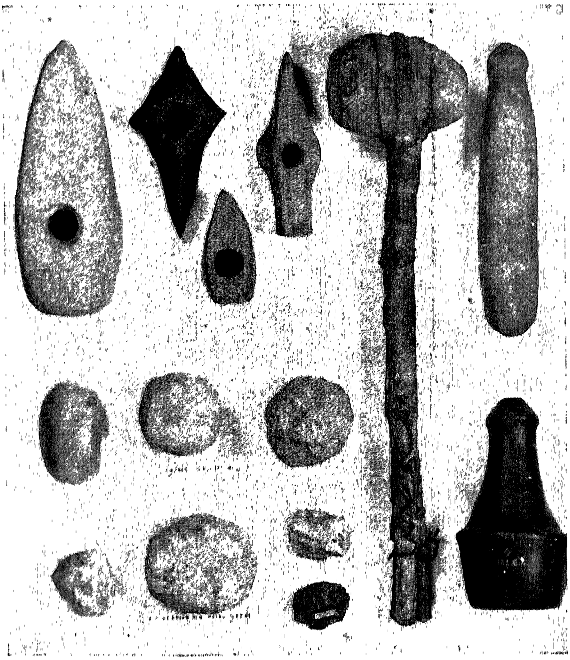
Section II

MATTER

CHAPTER IV

PROPERTIES OF MATTER

All scientists are concerned with matter in its various forms. The biologist studies living matter and its processes, the chemist studies the multitude of compounds of which matter is comprised, the geologist studies the changes that have taken place in the matter that forms the earth's crust, the physicist studies the relations between energy and matter and the ultimate nature of matter, etc.



(*American Museum of Natural History.*)
Fig. 98. Implements of the Stone Age.

Actually, all human activities are associated in some way with matter. The history of the progress of civilization is largely an account of man's increasing knowledge of matter, extending from

prehistoric times, when he gradually learned to use wood, stone, then iron, to the modern period, when our food, clothing, buildings, communications, transportation, and virtually all aspects of life depend on our increased understanding of matter.

Since matter is the basic working material in our world, we ought to learn as much as possible about it. In this section of our investigation of science we shall consider matter chiefly from the point of view of the physicist, although the fundamental concepts and ideas carry over into all other sciences.

THE THREE STATES OF MATTER

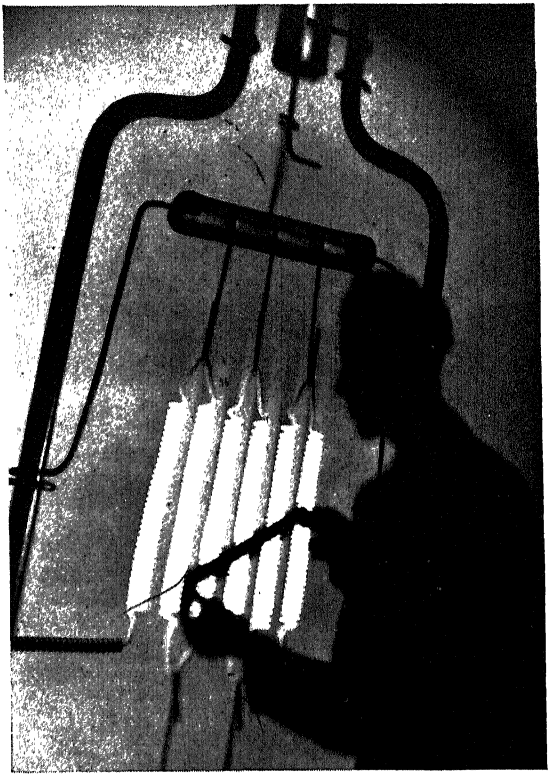
Solid, Liquid, and Gas. Even a casual examination of our surroundings shows that matter may exist in *three* fundamental states, *gaseous, liquid,* and *solid.*

Can every substance exist in all of the three states? Certainly many substances can. Water may exist as a solid—ice—as a liquid, and as a gas—steam—depending on its *temperature* and *pressure.* In fact, the state of a substance depends only on the temperature and the pressure to which it is subjected. For example, ordinary air (nitrogen 78 per cent, oxygen 21 per cent, and rare gases 1 per cent) condenses completely to a liquid if the temperature is lowered to 321 degrees below zero Fahrenheit (−196° centigrade), and becomes a solid if the temperature is further lowered to −360°F (−218°C).[1] If the pressure is increased above normal atmospheric pressure, the corresponding temperatures required to produce the liquid and solid states need not be so low. All gases in nature can be made to change state in a similar manner, but the temperatures (at a definite pressure) at which they boil and freeze, of course, are different. The other extreme of the range of boiling and freezing temperatures belongs to the metal tungsten of which electric lamp filaments are made. This metal becomes a liquid if the temperature is raised to 6100°F (3400°C), and it becomes a gas if raised to 10,600°F (5900°C). All other solids can be changed to gases by heating, although many compounds decompose before the temperature is high enough to vaporize them.

Temperature and Life. The accidental conditions of temperature and pressure that exist on earth are indeed fortunate for us. Tempera-

[1] See p. 163 for temperature scales.

tures in the universe extend all the way from −488°F (−271°C) to as high as 36,000,000°F (20,000,000°C) and perhaps beyond, but conditions favorable for the existence of life as we know it can hardly be outside of a comparatively narrow range of temperature,



(*Westinghouse Electric and Manufacturing Company.*)

Fig. 99. Greatly enlarged projection of a lighted lamp filament of tungsten.

possibly from about 32°F (0°C), the freezing point of water, to 120°F (49°C).

The temperature balance in our terrestrial environment is quite critical, for geologists tell us that a decrease in average temperature of only a few degrees would gradually bring on another ice age!

DESCRIBING MATTER

What properties of matter are really important? The answers of the chemist, the biologist, and the physicist to this question would naturally differ in emphasis, but in their main points all would

agree. Let us glance at some of the more fundamental of these characteristics of matter. In order to do this, however, we must be able to describe phenomena on a reasonably scientific basis. To make accurate description possible it has been essential for scientists everywhere to agree on a common terminology in which words and terms are given precise and limited meanings, rather than the loose interpretations in common use. Unless accurate definitions can be given, no field of investigation can really be called a science.

Furthermore, we must have a system of standards for accurate quantitative measurements, in which the units are defined as exactly and unambiguously as possible. Of course it should be understood that scientists are always ready to revise the meaning of terms or the standards of measurement to agree with new advances in knowledge.

Mass, Length, and Time. Probably the most fundamental of physical concepts that we use are ***mass, length,*** and ***time.*** Moreover, combinations of these can be used to express all other physical quantities. We have learned that all ancient civilizations evolved systems of weights and measures as matters of practical necessity. Today scientific workers, to describe mass and length, use the metric system of units almost exclusively. The fact that this system is naturally adapted to the expression of measurements in terms of decimals adds greatly to its convenience. Corresponding to inch, foot, or mile in the English system, the unit of distance in the metric system is usually taken as the ***centimeter,*** the ***meter*** (100 centimeters), or the ***kilometer*** (1,000 meters). Similarly, the metric unit of mass is commonly either the ***gram*** or the ***kilogram*** (1,000 grams).[1]

In nearly all countries except England and the United States the metric system is used for everyday as well as scientific purposes. Here we still cling to the cumbersome English system for common use, but legally our inch and pound are now defined in terms of

[1] The metric system, when the units centimeter, gram, and second are emphasized, is commonly called the CGS system. If the meter, kilogram, and second are stressed, it is called the MKS system. Partly because the meter and the kilogram are of a more practical size than the centimeter and gram, and partly because of the simple relationships between quantities defined in terms of the meter and kilogram, there has been a growing tendency to use these quantities in a consistent system of units. We shall in most cases find it convenient to use this system of units.

the meter and kilogram. Gradually we are adopting the metric system; for example, our distances in athletic track events are now often specified in metric units, the 100-meter dash rather than the 100-yard dash, etc. In spite of the great simplicity of the metric

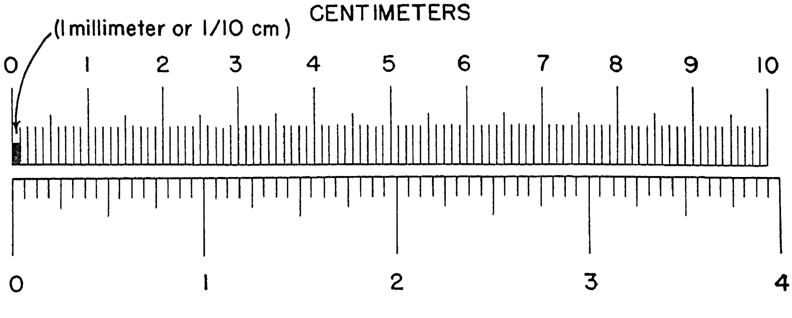


Fig. 100. Inch and centimeter scales showing relative sizes of units.

system, it will be some time before we use it completely in this country; indeed, it probably is not desirable to change to it suddenly. However, because of its advantages, we shall use the metric system in most of our work.

Length. The meter, of which the centimeter is one-hundredth part, was originally intended to be one 10-millionth of the distance from the equator to the pole, but the measurement of this distance in the French Revolution period, when the meter was originally defined, was not so accurate as those made later. The International Prototype Meter, now in use, is the distance, at 0°C, between two fine parallel lines on a bar carefully prepared and preserved at the International Bureau of Weights and Measures at Sèvres, near Paris. Accurate duplicate standards are kept at our National Bureau of Standards in Washington, D. C., and in other countries. In the United States, according to a recent law,

$$1 \text{ inch} = \text{exactly } 2.54 \text{ centimeters or } 0.0254 \text{ meters}$$

thus

$$1 \text{ foot} = 0.3048 \text{ meters}$$

or

$$1 \text{ meter} = \text{approximately } 39.37 \text{ inches}$$

Mass. We have already used the term *mass* in our discussions of the development of astronomy (page 59), but we must now con-

sider it more carefully, especially in distinguishing mass from weight. Unfortunately several methods for defining weight and mass have arisen within both the metric and English systems. Each method has certain advantages, but it is essential to use one of them consistently, as we shall do.

By the mass of a body we mean the ***quantity of matter*** it contains. This will clearly be the same anywhere in the universe. The arbitrary standard of mass is the International Prototype Kilogram (1,000 grams), a block of platinum-iridium alloy carefully preserved at Sèvres, France. This was intended to be exactly equal to the mass of 1,000 cubic centimeters (1 liter) of water at its temperature of maximum density (4°C), but actually it differs from this by a very small amount. Duplicate standards are also kept at the Bureau of Standards and in other countries.

Weight. By the ***weight*** of a body we mean the force with which it is attracted toward the earth. The concept of ***force*** is quite intuitive, and is frequently associated with the sense of muscular effort in pushing or pulling on various objects. It takes a larger force to lift a man than to lift a child, a larger force to lift two books than one alone. From Newton's law of gravitation, this force of attraction of the earth for the body, the weight, is given by

$$F = G\,\frac{M_1M_2}{d^2}$$

where M_1 is the mass of the earth (about 5.95×10^{24} kilograms), M_2 is the mass of the body, d the distance between the center of the body and the center of the earth (usually about 6.36×10^6 meters), and F the force or the ***weight*** of the object. Here G is a constant which depends on the units in which the various quantities are measured. Many physicists have recently agreed to use a new unit of force or weight, the ***newton***.[1] In order to express the attractive force in newtons between two bodies when the masses are in kilograms and the distance of separation is in meters, the constant G must be

$$G = 6.66 \times 10^{-15}\,\frac{\text{newton-meter}^2}{\text{kilogram}^2}$$

The value of G was first obtained by Cavendish in an ingenious experiment in which he actually measured the force of attraction

[1] One way of expressing the newton is to say that it is the force that would give a mass of 1 kilogram an acceleration of 1 meter per second per second.

between two objects in his laboratory. The weight of a piece of matter depends on its position on the earth's surface, because the distance to the earth's center, d, varies somewhat with position. Although this variation is quite small, a body weighs slightly more at sea level than on a mountain top. Some instruments are so sensitive that they can detect the difference in the weight of a suspended object when the supporting thread has been shortened as little as 2 in. If a body were taken up 4,000 miles from the earth's surface its weight would be reduced to one-fourth. Since the weight of a body is proportional both to its mass and to the quantity $G\frac{M_1}{d^2}$ (or, more briefly, g), we can say that

$$W = gM \qquad \text{or} \qquad M = \frac{W}{g},$$

where M is the mass in kilograms, W is the weight in newtons, and g is a quantity which expresses the ***gravitational attraction*** at the object's position,[1] and its numerical value on the earth's surface is approximately 9.80 meters per second per second, or, in shorthand, 9.80 meters/sec^2. On account of the flattening of the earth at the poles, g varies from 9.8321 meters/sec^2 there, to 9.7799 meters/sec^2 at the equator. A force, or weight, is thus expressed in newtons, and to obtain it we must multiply the mass in kilograms by g. In other words, a mass of 1 kg weighs about 9.8 newtons on the surface of the earth.

In the ***English system*** we take as our unit of weight, or force, the ***pound***. We shall not use any special name for the unit of mass in that system, but it should be clear that if the weight, W, of an object is expressed in pounds (lb) then the mass, M, is obtained by the relation $M = W/g$. Here g must be expressed in appropriate English units, approximately 32 feet per second per second, or 32 ft/sec^2.

Although common usage is very loose, we must always be careful not to confuse mass and weight. A typical equal-arm balance (no springs) compares the ***mass*** of an object with a standardized set of masses and will give accurate mass values anywhere. Of course this also measures the relative weights, but in order to obtain the actual weight of the object, the value of g at the place of the measurement must also be known. However, since g varies by only small amounts

[1] g is also the acceleration of a freely falling object.

over the earth's surface, the weight of the object can be estimated for most practical purposes by such a balance, even though g is not actually measured. On the other hand, if a simple spring balance could be calibrated accurately at one spot, it would give accurate

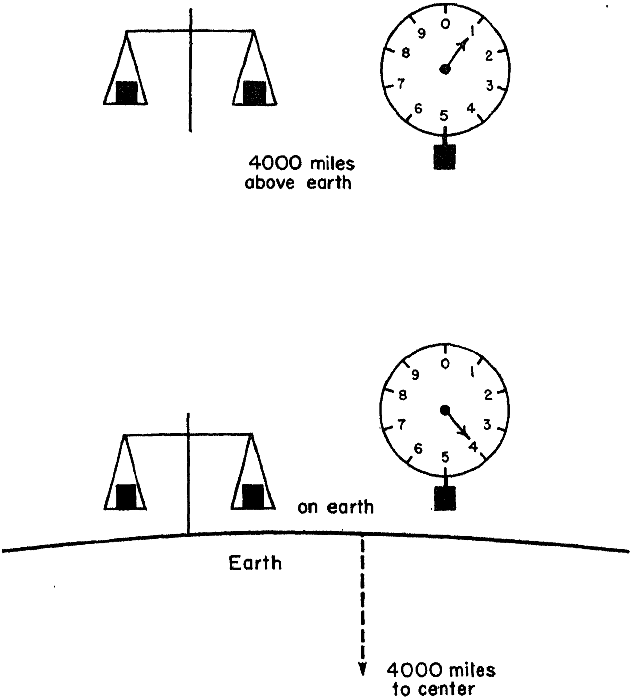


Fig. 101. The reading of a beam balance would not change with increasing distance from the earth, because equal masses on the two arms remain balanced regardless of the force on each. A spring balance (represented by the dial) gives readings that would decrease with increasing distance from the earth, because its deflection is proportional to the force or weight.

weight values everywhere else, since it measures directly the attractive force of the earth on the object.

Time. We learned earlier that all time measurements are based on the time required for the earth to make one rotation on its axis. Astronomers naturally use ***sidereal time*** or "star time," in which one rotation with respect to the "fixed stars" is 24 hr (page 81). But for civil and most scientific purposes we use ***mean solar time*** in which 24 hr, or 1,440 min, or 86,400 sec, is the average time for one rotation of the earth on its axis with respect to the sun. Time units are of course the same in both metric and English systems.

Length, Mass, and Time as Fundamental Units. Nearly all scientific observations are based fundamentally on the concepts of mass, length, and time. In the future we shall also meet many new units of measurement. These will be used sometimes for purely historical reasons, and sometimes because new phenomena can be more directly described by introducing new concepts, but in general all units will be closely related to these three basic concepts of mass, length, and time.

SOME TYPICAL PROPERTIES OF MATTER

Let us now survey briefly some of the typical properties of matter in order to see what sort of phenomena the physicist, the chemist, and the biologist would like to describe. Many of these properties we shall consider again at later times when a more complete background will permit us to understand them better.

Density. Even the handling of pieces of various kinds of matter, such as wood and iron, shows that these materials may differ greatly. In order to express such differences more definitely, the concept of ***density*** is useful. The density of a material is its mass per unit volume. Expressed in mathematical shorthand,

$$D = \frac{M}{V}$$

If we measure the mass, M, in grams, and volume, V, in centimeters^3 (cubic centimeters), then density, D, is expressed in grams per cubic centimeters (g/cm^3), that is, the number of grams in one cubic centimeter of the material. As we consider mass to be "quantity" of matter, it is obvious that the idea of density, or mass per unit volume, is applicable to all three forms of matter, solid, liquid, and gaseous. It is clear that the volume of a given mass of material depends on the temperature and pressure, particularly in the gaseous state.[1] Consequently, these two conditions must be specified in giving density values. For gases, a standard set of reference conditions which will become familiar to us later, called normal temperature and pressure (abbreviated NTP), are 0°C and the pressure exerted by a 76.0-cm column of mercury.

The following table gives an idea of the range of density values of typical materials.

[1] See Chap. XII on the gas laws.

DENSITY OF SOME COMMON MATERIALS

Solids

Name	Density, g/cm³ at 20°C
Aluminum	2.70
Brass, yellow	8.6
Carbon, graphite	2.25
Coal	1.2–1.8
Copper	8.9
Glass:	
Common	2.4–2.8
Flint	2.9–5.9
Gold	19.3
Granite	2.65–2.7
Iron	7.9
Lead	11.3
Magnesium	1.74
Platinum	21.4
Quartz	2.65
Sandstone	2.2–2.6
Table salt (NaCl)*	2.17
Tungsten	19.3
Wood (seasoned):	
Balsa	0.11–0.14
Ebony	1.1–1.3
Oak	0.6–0.9
Pine, white	0.35–0.5
Zinc	7.1

Liquids

Name	Density, g/cm³ at 20°C
Bromine	3.12
Carbon disulfide (CS_2)	1.26
Carbon tetrachloride (CCl_4)	1.59
Ether	0.72
Ethyl alcohol	0.79
Gasoline	0.7–0.8
Mercury	13.55
Petroleum oil (crude)	0.8–1.0
Sea water	1.025
Water	0.998 (1.000 at 4°C)

Gases

Name	Density, g/cm³ at NTP
Air (dry)	0.001293
Carbon dioxide (CO_2)	0.001977
Helium (He)	0.0001785
Hydrogen (H_2)	0.0000899
Nitrogen (N_2)	0.001251
Oxygen (O_2)	0.001429
Radon (Rn)	0.00973

* See Chap. V for meaning of chemical symbols.

Mechanical Properties. *Elasticity.* Materials differ strikingly in their mechanical properties. When a thin strip of steel is released after being bent moderately, it springs back into its initial position. A similar strip of lead bends much more easily but when released it returns to its original position only if the bending has been very slight. Virtually every object is ***elastic;*** that is, when bent, compressed, twisted, or otherwise deformed, it develops internal forces which tend to restore it to its initial form.

If the deformation of an object is carried to such an extent that the material does not resume its initial form when the force is removed, we say that the process went beyond the ***elastic limit.*** Elastic characteristics of materials are exceedingly important in

construction engineering. Many types of springs are utilized in diverse mechanisms, ranging from automobiles to watches. Elasticity makes possible most of the vibratory motion in nature. The vibrations of musical instruments, the transmission of sounds

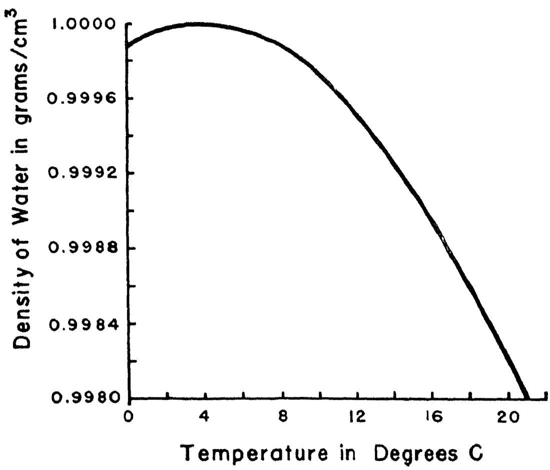


Fig. 102. The density of water is a maximum at 4°C.

through the air, and even the "to and fro" motion of the leaves on the trees, all depend upon the elastic properties of the vibrating materials.

Robert Hooke was the first to demonstrate the simplicity of the basic law of elasticity. Let us rediscover his conclusions by performing a simple experiment. Suppose that we support a coil spring so that its lower end is originally at the point A (Fig. 103), and then see how the displacement x of the lower end of the spring changes when we attach various weights or loads. The following table shows a record obtained by such an experiment in the laboratory. The results are also represented graphically in Fig. 104.

Weight, Newtons	Displacement, Meters
0.000	0
0.196	0.053
0.392	0.106
0.588	0.158
0.784	0.211
0.980	0.265

According to these results, the increase in length of the spring is quite accurately proportional to the weight or force on the end of the spring. If we double the force, the displacement doubles; if we

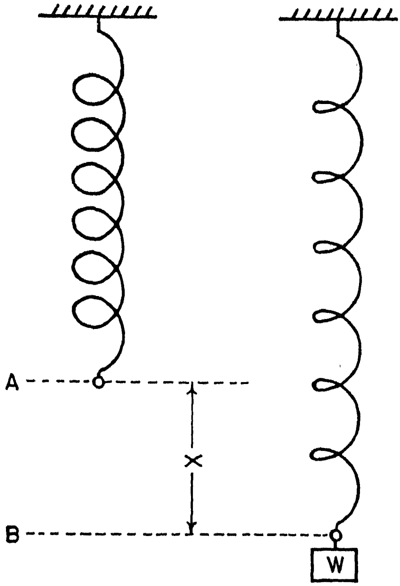


Fig. 103. Loaded spring.

triple it, the displacement triples, etc. On the graph the points lie on a straight line, so we say that the relationship between the two factors is a linear one. The accurate description of a natural phenomenon often turns out to be astonishingly simple when we perform the right type of ***controlled quantitative experiment*** to reveal it.

The generalization of the result of our experiment, known as Hooke's law, may be expressed very simply in a mathematical form

$$F \propto x$$

where $\propto$ means "proportional to;" or

$$F = kx$$

where k is a constant, the ***elastic constant*** of the spring. F is the force exerted by the spring tending to return to its initial form, and

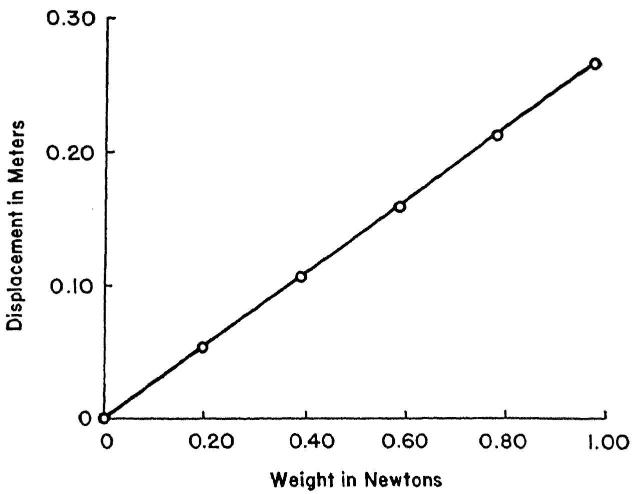
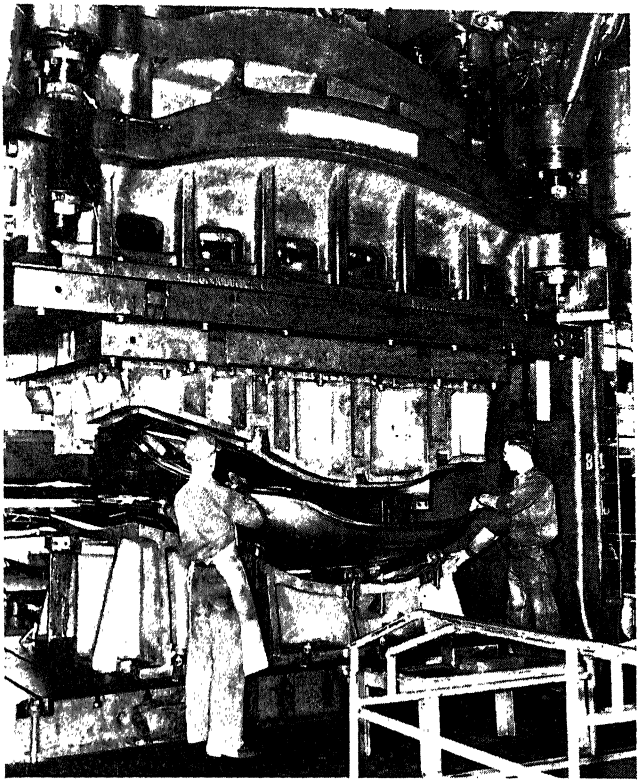


Fig. 104. The stretch of the spring is proportional to the attached weight.

is obviously directed ***opposite*** to the displacement. Since F (or Mg) is measured in newtons and the displacement is in meters, k is given

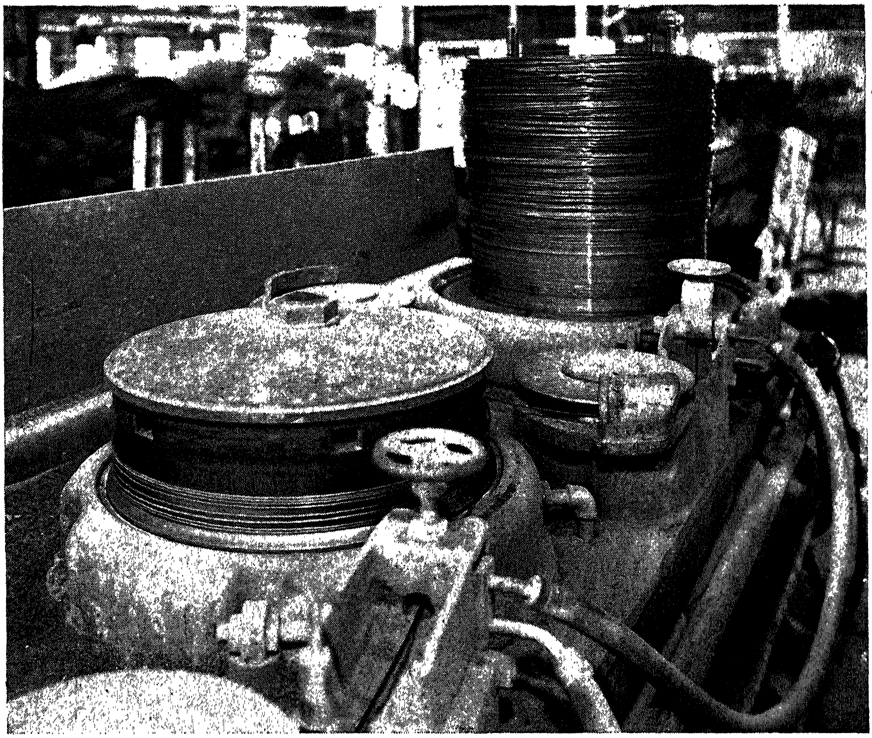
in newtons per meter. For the spring tested, k is approximately -3.7 newtons/meter. Such a calibrated spring may be used as a spring balance and measures weight (force), not mass, because its reading depends on the gravitational attraction and hence varies slightly with position on the earth.



(*General Motors Company.*)

Fig. 105. Large press for forming steel automobile tops.

Malleability. There are many other so-called mechanical properties of matter. ***Malleability*** refers to the ease with which a material may be shaped into any desired form by hammering or by passing between rollers. A soft metal such as gold may be pounded readily into a sheet so thin (perhaps 0.00001 in.) that it becomes partially transparent. Metals such as platinum may be rolled into sheets less than 0.0001 in. (0.00025 cm) thick, which are so nonporous as to be vacuum-tight. Long before the Christian era, the discovery that iron could be "worked," especially when hot, made possible the construction of useful tools. Today those metals which



(*Roebling.*)

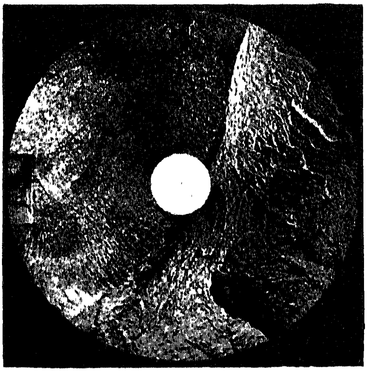
Fig. 106. Wire drawing machine. Steel wire is formed by being drawn through a series of progressively smaller holes in water-cooled dies which reduce the size by stages.

can be stamped, pressed, or rolled into various forms without breaking are the basis of much of our mass production system. Automobile bodies are now stamped out of virtually one piece of metal by giant presses.

Ductility. *Ductility* is a property closely related to malleability. Ductile materials can be "drawn down" into fine wires by pulling them through progressively smaller holes or "dies." Steel and copper are quite ductile. Even tungsten, a hard, brittle metal, can be drawn into wires less than 0.001 in. (0.0025 cm) in diameter; yet this has not been possible without careful research on the preparation of tungsten in a homogeneous form. Our present-day tungsten-filament lamps represent one of the benefits derived from a thorough study of a problem in ductility.

Tensile Strength. To the engineers who build suspension bridges or set up power lines, an important property of the materials

they use is ***tensile strength.*** Most substances stretch elastically within small limits, but when the applied force becomes large enough, the internal forces that hold the material together are overcome, and the substance pulls apart. Lead, of course, has a very



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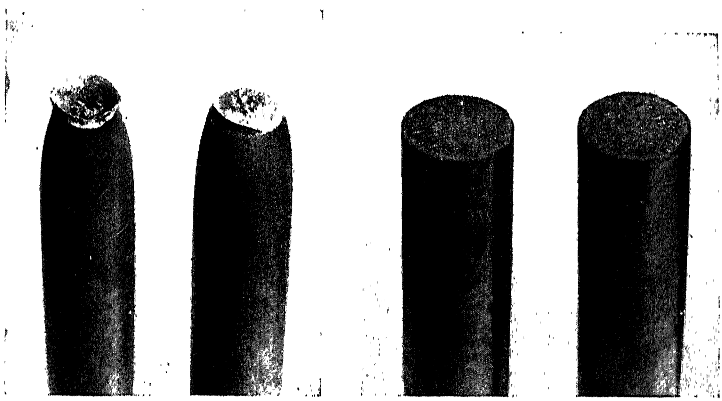


b c

(*Kehl, The Principles of Metallographic Laboratory Practice.*)

Fig. 107. Fractures of steel shafts. (a) "Fatigue" fracture of 6-in. drive shaft. (b) Tensile fracture of ductile steel. Note cup-cone form of ends. (c) Tensile fracture of relatively non-ductile steel. Note absence of cup-cone form of ends.

low tensile strength, while steel has one of the highest. Under some conditions quartz (fused silica or sand—SiO_2*) is one of the strongest materials known. A quartz fiber almost invisible to the naked eye will support several pounds.

In engineering it is also necessary to consider other types of strength factors, such as ***resistance to crushing, yield points*** for

* See Chap. V for meaning of chemical symbols.

loaded beams, and ***torsional strengths*** of rotating shafts used to transmit power.

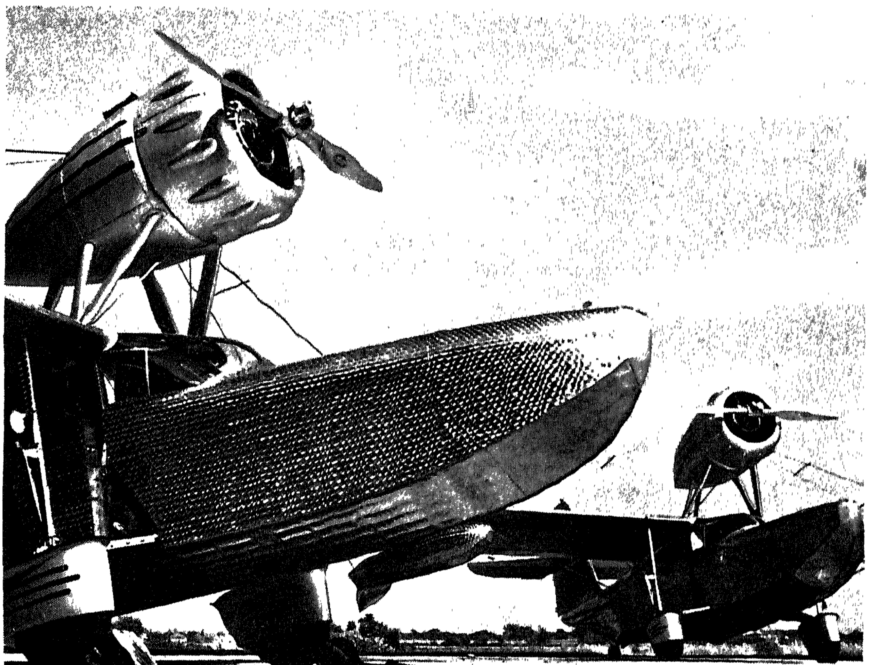
Hardness. The geologist studying the rocks and materials of the earth's crust, and the metallurgist developing new metals to withstand wear or erosion, are greatly concerned with ***hardness.*** One crude way of estimating hardness makes use of the fact that a piece of material can be "scratched" by any harder material. Diamond is the hardest substance known and, therefore, can "scratch" any other material. Substances often used for hardness tests, arranged in the order of increasing hardness, are (1) talc, (2) rock salt, (3) calcite, (4) fluorite, (5) apatite, (6) feldspar, (7) quartz, (8) topaz, (9) corundum, (10) diamond. On this scale, lead is about 1.5, copper about 2.5 to 3, and steel about 5 to 8.5. More elaborate hardness-test methods (such as the Brinnell system) measure essentially the distance a small hard ball will press into a substance when under a definite applied force.

Viscosity. To the man who drives a car, to the lubrication engineer, and to the chemist, the ***viscosity*** of liquids, of semisolids, and even of gases is particularly important. This property also belongs to some substances frequently considered to be rigid solids, for example, glass and wax. Anyone who has tried to pour motor oil, or the traditional molasses, at subzero temperatures is much impressed with viscosity and its marked dependence on temperature. Viscosity is often measured by the time it takes a given amount of liquid (or gas) to pass through a long tube of standard radius when there is a standard pressure difference between the two ends of the tube. The viscosity of substances has a tremendous range of values. Hydrogen is one of the least viscous gases, and gases in general are about one-thousandth as viscous as typical liquids such as water. Ether is one of the least viscous liquids. According to an agreement by the Society of Automotive Engineers, motor oils are now given viscosity (S.A.E.) ratings. Oils that are commonly used in automobiles range from about S.A.E. 10 (light winter oil) through S.A.E. 30 (so-called medium) and on up to S.A.E. 60. Semifluid oils or greases range to greater than S.A.E. 250.

New Materials. The addition of small amounts of other substances often produces marked changes in the properties of a metal, particularly when the resulting ***alloy,*** or mixture of metals, is given special heat treatment. Today the purpose of much research by

(*Courtesy of Product Engineering.*)

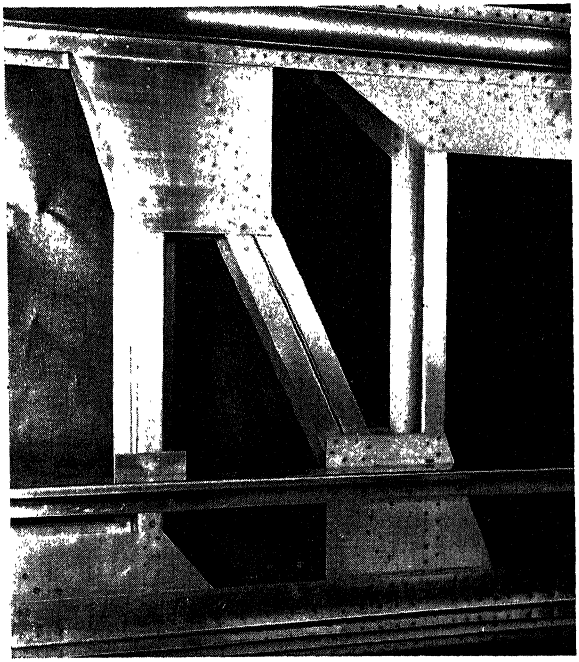
Fig. 108. Modern lightweight train built of duralumin and insulated with Fiberglas. Powered by 2,000 HP Diesel-electric locomotive ("Southern Belle" of the Kansas City Southern Lines).



(*Courtesy of American Machinist.*)

Fig. 109. Stainless-steel aircraft ("Sea Birds" built by Fleetwings, Inc.)

metallurgists, chemists, and physicists is to develop new materials with special mechanical properties, and to improve old materials. They have developed many new alloys with remarkable characteristics. Some of these alloys have already revolutionized industries.



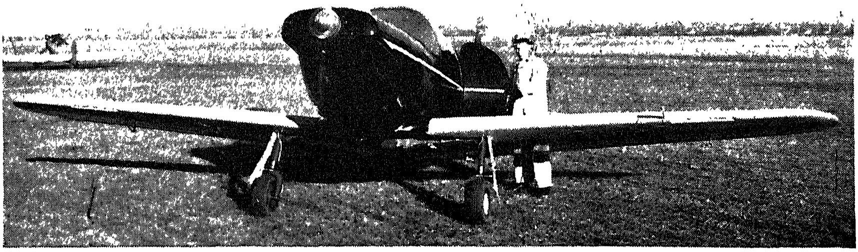
(*Budd.*)

Fig. 110. Typical spot-welded stainless-steel construction in the framework of a lightweight railroad car.

Duralumin, for example, an aluminum alloy in which the principal addition is a small amount of copper, has the low density of aluminum but has a strength comparable with that of steel. It is widely used where minimized weight is important, as in airplanes.

Many varieties of so-called ***stainless steel,*** usually iron with chromium, nickel, and other elements, are now made not only resistant to rust or chemical corrosion but often stronger than the old steels. When pressed or stamped into special reinforced forms such as trusses, girders, and ribbed surfaces, steel alloy structures may be made so strong and yet so light that they are now widely used in airplane and light "streamlined" train construction in place of aluminum alloys.

Although pure copper has a comparatively low tensile strength, tiny amounts of the element beryllium alloyed with it increase its



(*Industry Illustrated.*)

Fig. 111. Molded plastic monoplane of Summit Aeronautical Company.

tensile strength to that of steel with little change in its important electrical properties.

Research in synthetic chemistry has led to the development of a group of materials called ***plastics,*** which are finding wide application under trade names such as Bakelite, Catalin, Textolite, and Lucite. These synthetic products may have their origin in all sorts of basic materials, in coal, in oil, in plants, or in the casein of milk. Easy to fabricate and mold into complicated forms, usually somewhat elastic, and occasionally subject to plastic viscous flow, yet strong and tough, these and even newer materials will find increasing use in the fabrication of everything from dishes and furniture to automobile bodies, airplanes, and even houses. We shall find countless examples of new and old substances made to serve man and to advance the technical aspect of his civilization.

Some Thermal Properties of Matter. *Measuring Temperature.* Our fundamental need for clothing and shelter indicates the importance to man of the thermal properties of matter. Until Galileo invented the first crude thermometer, only the untrustworthy sense of touch was available to measure what was then called the "degree of hotness." His thermometer depended upon the expansion of heated air, and changes of barometric pressure seriously affected its readings. In time men learned that almost all materials, when heated, expand by amounts which are nearly proportional to one another. Thus, for practical purposes, it has become customary to consider that

changes in temperature are proportional to the changes in volume of a quantity of material such as mercury or alcohol. Some sort of temperature scale is necessary, and to *calibrate* any thermometer in terms of this temperature scale, it is essential to have points of "fixed" temperature that can be duplicated. In the early period all sorts of fixed points were used, among them body temperature and the temperature of melting butter.

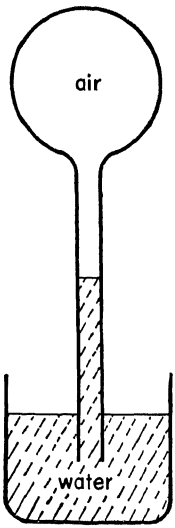


Fig. 112. Air thermometer of Galileo. A temperature rise causes the enclosed air to expand, forcing down the water level in the tube.

England and the United States still cling to the scale arranged by Fahrenheit, where 0°F was originally the lowest temperature obtainable with an ice-salt mixture, and 96°F was supposed to be body temperature. The melting point of ice, and the boiling point of water (at NP[1]), we now know to be much more satisfactory fixed points. These are taken to be 32 and 212 degrees respectively on the modern Fahrenheit scale, giving an interval of 180 degrees between them.

On the centigrade scale (first arranged by an astronomer, Celsius), the melting point of ice (at NP) is taken to be 0°C, and the boiling point (at NP) is 100°C, making a convenient 100-degree interval between the two fixed points. Since an interval of 180 degrees Fahrenheit is equivalent to an interval of 100 degrees centigrade, the centigrade degree is $9/5$ or 1.8 times as large as the Fahrenheit degree. A little consideration will show that to convert temperatures on one of these scales to temperatures on the other, the following relations hold:

$$\text{Degrees F} = \frac{9}{5}\,(\text{degrees C}) + 32$$

or

$$\text{Degrees C} = \frac{5}{9}\,(\text{degrees F} - 32)$$

The centigrade scale has supplanted all others for scientific work.

Thermal Expansion. We have noted the use of ***thermal expansion*** for the measurement of temperature. This property of matter is important in other ways than its application to thermometry.

[1] Normal atmospheric pressure—76 cm Hg.

The Empire State Building is about one foot higher on hot summer days than on cold winter days because of thermal expansion. Such changes must be considered in design. Fortunately, it is possible to determine these changes accurately from a simple fact which was

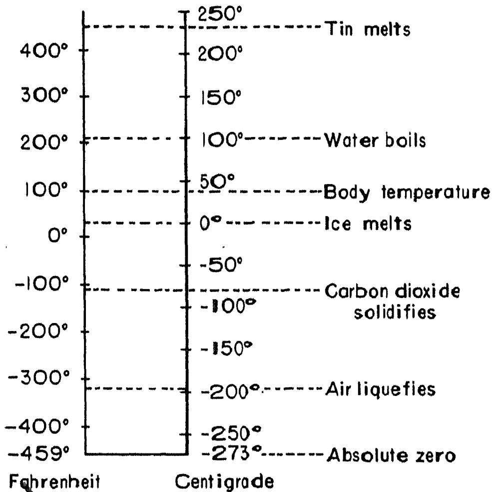


Fig. 113. Centigrade and Fahrenheit temperature scales.

mentioned before: Over moderate ranges of temperature the ***change in length of almost every piece of material is proportional to the temperature change.***

It is apparent that the change in length is proportional also to the initial length. For example, a 2-ft rod will expand twice as much as a 1-ft rod. If we call the original length L_0 and the temperature change $t_1 - t_0$ (that is, the difference between the final temperature t_1 and the initial temperature t_0), then the above two statements may be combined in the mathematical form

$$\text{Change in length} \propto L_0(t_1 - t_0)$$

or

$$\text{Change in length} = aL_0(t_1 - t_0)$$

where a is a constant of proportionality which is named the ***coefficient of linear expansion.***

Therefore, to each material it is possible to assign a ***coefficient of linear expansion,*** a, for which the last equation gives

$$a = \frac{\text{change in length}}{L_0(t_1 - t_0)}$$

Thus, a is the fractional change in length per degree change in temperature.

If the final length is called L_1, the change in length is $L_1 - L_0$, so that

$$L_1 - L_0 = aL_0(t_1 - t_0)$$

Then the final length is

$$L_1 = L_0 + aL_0(t_1 - t_0)$$

So if we know the initial length and the temperature change, we can calculate very simply the change in length and the final length. Of course we must obtain from the proper tables the standard value of the coefficient of expansion for the material involved.

Some typical coefficients of linear expansion ***per degree centigrade*** are listed in the following table.

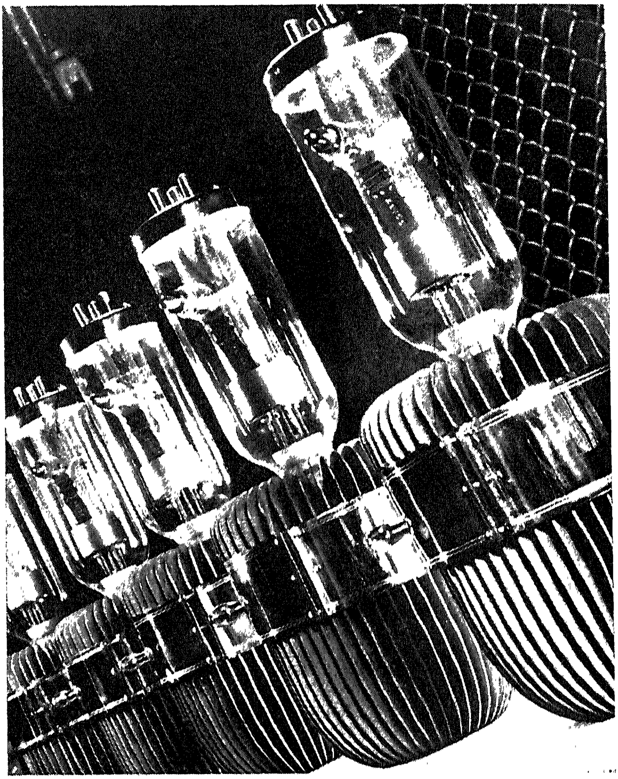
COEFFICIENTS OF LINEAR EXPANSION OF SOME COMMON MATERIALS

Material	Coefficient of Linear Expansion a at 20°C, per °C
Aluminum	23.0×10^{-6}
Brass, yellow	18.9×10^{-6}
Copper	16.6×10^{-6}
Glass:	
Ordinary	8.5×10^{-6}
Pyrex	3.6×10^{-6}
Ice (−20°C to −1°C)	51.0×10^{-6}
Iron	11.7×10^{-6}
Invar	0.9×10^{-6}
Porcelain (electrical insulators)	3.5 to 5.5×10^{-6}
Quartz, fused	0.4×10^{-6}
Steel	9.6 to 10.3×10^{-6}
Wood:	
Oak (along grain)	4.9×10^{-6}
Oak (across grain)	54×10^{-6}

On a very hot summer day the cables on the George Washington Suspension Bridge may reach a temperature of 105°F. On a cold night their temperature occasionally gets down to −12°F. This is a change in centigrade temperature of $\frac{5}{9} \times$ (117°F), or 65°C. The length of a cable is about 6,000 ft. If we substitute these figures in the relation for change of length with temperature, taking the coefficient of linear expansion per degree centigrade from the table, we have for the extreme change in length of one of the cables:

$$L_1 - L_0 = 6{,}000 \text{ ft} \times \frac{0.000011}{°\text{C}} \times 65°\text{C} = 4.3 \text{ ft}$$

It is interesting to note that, while iron and nickel have expansion coefficients that are quite typical of metals, the mixture of 36 per cent nickel with 64 per cent iron has only about one-fifteenth the expansion coefficient of either constituent. Naturally this alloy



(Westinghouse Electric and Manufacturing Company.)

Fig. 114. Large air-cooled transmitter tubes. Several metal-glass seals are involved in each tube. Photograph by Berenice Abbott.

(Invar) has many uses where it is important that changes of length with temperature be small, such as for pendulums of accurate clocks. Invar is too expensive for most purposes, so bridges, highway pavements, buildings, electric power lines, steam pipes, etc. must be designed to allow for expansion.

Joining metal to glass formerly presented a problem because the unequal contraction of metal and glass during cooling introduces strains that cause the glass to crack unless the metal is very thin. Now such a junction is easily made by using an alloy, usually of

iron and nickel, that has almost exactly the same coefficient of expansion as the glass. Therefore, even thick pieces of glass and these alloys can be joined together in mass production processes such as the manufacture of metal vacuum tubes.

Steel rails formerly were left with a gap between sections to allow for expansion. In more recent construction they are welded in one long piece, but fastened in place so securely that the rails cannot buckle when hot and compressed or pull loose when cold and under tension.

Melting and Boiling Points. Very important characteristics of each kind of matter are its melting point and its boiling point, that is, the temperature at which the solid state changes to a liquid, and the temperature at which the liquid changes to a gas (or the converse—liquid to solid, and gas to liquid). Practically all matter may exist in each of the three states provided it does not decompose at high temperatures, but the temperatures at which the changes of state occur differ greatly for the various materials. As melting points and boiling points depend upon the pressure, the values in the following table are for normal atmospheric pressure.

MELTING POINTS AND BOILING POINTS OF VARIOUS SUBSTANCES

Substance	Melting point at NP, °C	Boiling point at NP, °C
Aluminum	660	1800
Carbon dioxide	− 57*	Sublimes at −79
Copper	1083	2300
Ether	−116	35
Ethyl alcohol	−117	78
Glycerin	17	291
Gold	1063	2600
Helium	−272.2†	−269
Hydrogen	−259	−253
Lead	327	1620
Mercury	− 39	357
Nitrogen	−210	−196
Oxygen	−218	−183
Platinum	1773	4300
Quartz	1470	2230
Table salt (NaCl)	804	1413
Tungsten	3370	5900
Water	0.00	100.00

* Carbon dioxide cannot exist as a liquid below 5.2 atm.

† Helium cannot exist as a solid below 22 atm.

Water has one unique but important peculiarity: it expands upon freezing. If it were to contract when it freezes, as do most substances, the frozen parts of oceans and lakes would fall to the bottom and freezing would then continue until many of our water

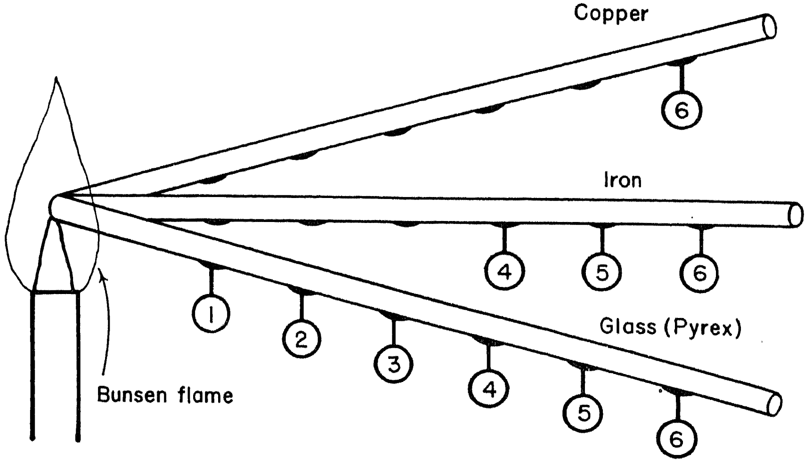


Fig. 115. Waxed tags drop most rapidly from the best conductor of heat.

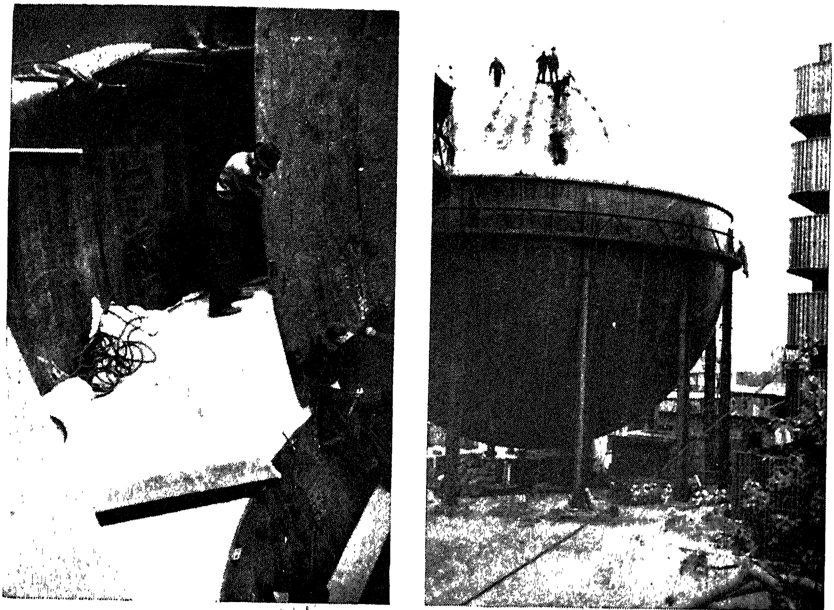
bodies would become solid, killing fish and marine life. In most places probably only the surface water would ever melt.

The energy changes and the changes in structure which occur when substances pass through the solid-liquid-gas transitions make an interesting story which can be told later.

Thermal Conductivity. The ***thermal conductivity*** of matter is vital to animals which require protection from extreme surrounding temperatures. All solids, liquids, and gases conduct heat, but enormous differences exist in the rate at which heat is transferred through them under similar circumstances.

A crude experiment serves to illustrate this statement. If we wax numbered tags on copper, iron, and glass rods of the same diameter, and heat the ends of all three equally, the transfer of heat along the rods will in time melt the wax so that successive tags drop off, the rapidity depending on the rate of heat conduction. In an actual experiment, the situation at the end of one minute is shown in Fig. 115. Five of the tags on the copper have dropped off, only three from the iron, and none from the glass, illustrating the great differences in the thermal conductivities of the three materials.

Metals have high conductivity (for samples of a given size), with silver the highest, copper about $9/10$ that of silver, and iron



(*Chemical and Metallurgical Engineering.*)

Fig. 116. Storage sphere for liquefied natural gas at —160°C. The sphere has a double wall with an insulating space between the two sections. It will hold 600,000 gallons of liquid, equivalent to 50 million cubic foot of gas. At left: assembly of the inner sphere after cork insulation has been placed. At right: Inner sphere completed with upper half of outer sphere still to be constructed.

having but 1/6 the conductivity of silver. For many purposes such as building construction we usually want ***insulators,*** that is, the poorest possible conductors. Many types of heat insulators have been developed by following the general rule that increasing the porosity of a substance usually increases its insulating properties. Several commercial materials, such as rock wool, Sil-o-cel, Celotex, and cork board, have relative heat conductivities about 1 /10,000 that of silver; all have low density and are porous. Glass and building brick are only fair insulators.

The animals were certainly well designed, for they are equipped with insulating coats that are even better than the specially developed insulators mentioned above. The best nonconductor is of course nothing at all, that is, space free from matter; accordingly, the air is evacuated from the space between the glass walls of a Thermos bottle. In Chap. VII on heat energy we shall learn more about the nature of heat, and, later, the great contribution by heat energy to our industrial life.

Some Optical Properties of Matter. Another interesting group of characteristics of matter might be called optical properties because they depend upon the interaction of matter and light.

Reflection and Transmission of Light. When a beam of white

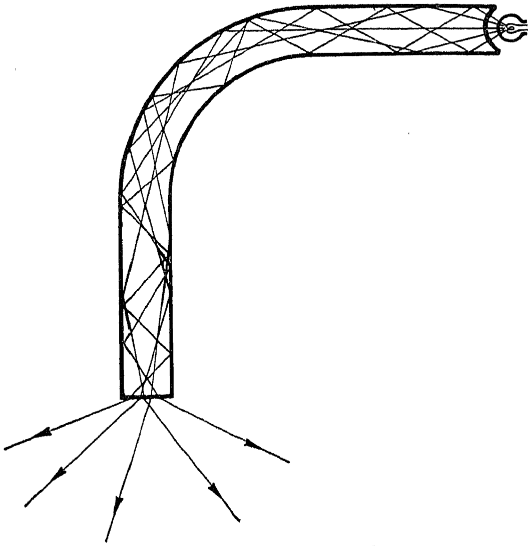


Fig. 117. Lucite serves as a light guide. Successive internal reflections keep much of the light inside the rod until the end is reached. If the index of refraction were lower more light would escape through the side walls.

light falls upon any substance, some of the light is ***reflected*** at the surface and some enters the material. If the substance is ***transparent,*** part of the light that enters the material passes through it. If the material is ***opaque,*** the light is ***absorbed.*** Even in metals, however, thin layers are transparent. Some materials, such as quartz or the new plastic Lucite, are so transparent that a beam of light that enters one end of a rod is transmitted through the material so that it emerges from the other end almost undiminished. This remains true even if the rod is bent into all sorts of odd shapes, because light striking the sides of the rod at glancing angles is internally reflected so it can leave the rod only at an end. Light may literally be led or "piped" through these substances, and thus, for example, may be made to provide illumination for internal medical examination.

Color. One of the simplest ways to distinguish between various materials is by their ***colors.***

matter upon which it falls. We must inquire more deeply into the nature of matter and radiation before we can understand the mechanism of this interaction.

An Important Electrical Property of Matter. In this electrical age, the use of matter to conduct electricity is of almost inestimable value to us. That some substances conduct electricity while others do not has been known ever since Stephen Gray (1696–1736) and a friend showed that "hot pokers, live chickens, maps, and umbrellas" could be "electrified" at a distance of 650 ft if connected to the end of a line made out of certain substances, notably metals, supported by insulating silk threads.

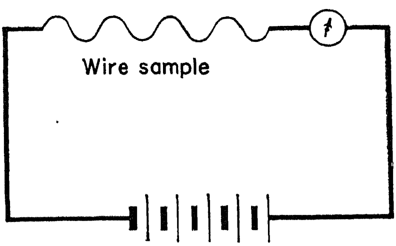


Fig. 119. Simple electrical circuit.

The relative *conductivities* of materials can be measured easily. Suppose that we take wires of copper, aluminum, iron, and lead, of equal lengths and diameters, and connect them in turn to a source of electric energy (for example, a battery), as in Fig. 119. The "pressure," or potential difference which forces the flow of electricity (electric current), is the same for all three materials because it depends only on the battery. An ammeter, a current-measuring instrument, can be placed in the electric circuit to show the current quantitatively, or, if we do not wish an accurate comparison, a small automobile lamp will do. (Note that current exists only when a complete circuit is established from one side of the battery, through the wires under test, and back again to the battery.) The magnitudes of the currents are very different in the four cases. In one such series of experiments the ammeter read:

For the copper wire	0.90
For the aluminum wire	0.61
For the iron wire	0.16
For the lead wire	0.08

The electrical conductivities of the wires are proportional to these numbers.

It is suggestive to compare the relative electrical conductivities of these metals with their thermal conductivities. The ratios between these two quantities are very nearly the same for these

metals. Clearly, there must be some interesting connection between thermal and electrical conductivity which we should investigate further.

It is of interest to notice that the relative conductivities of good conductors of electricity such as silver, copper, and aluminum may be as great as 10^{22} times those of insulators or nonconductors such as glass, quartz, and amber.

The conduction of electricity by matter makes possible the work of the electrical engineer and provides for the transportation of electric energy for use in homes, for communication, and so on. To the physicist it gives very important clues as to the nature of matter in its various states. We shall have occasion to learn much more about electrical conductivity in a number of succeeding chapters which deal with electrical phenomena.

We have made a brief survey of a few of the physical properties, some general, some specific, that enable us to describe matter. This list is far from complete, indeed it is not intended to be complete, but it should give us perspective and serve as a basis for further study.

It should already be clear that in order to understand these properties of matter in bulk—so-called ***macroscopic*** properties—we must consider the particles out of which matter is built, the molecules, the atoms themselves, and even the electrons and other component parts of the atoms.

FOR STUDY AND READING

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SUMMARY

Matter, the basic working material for all sciences, may exist in the ***solid, liquid,*** or ***gaseous*** states, depending on conditions of temperature and pressure.

For a quantitative description of properties of matter, there must be an accurate terminology and a system of standards and

units. Scientists have chosen ***mass, distance,*** and ***time*** as fundamental quantities, and use the metric system of units.

The mass of a body is its "quantity of matter." The body's ***weight,*** or the gravitational force on it, is

$$\text{Weight} = g \times \text{mass}$$

where g is the acceleration due to gravity. The weight is in ***newtons*** (a unit of force) when g is in meters per second per second (about 9.80 meters/sec^2 on earth) and mass is in kilograms.

The ***density*** of a material is defined

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

The unit grams per cubic centimeter is convenient. Densities of gases are usually listed at 0°C and the pressure exerted by a 76-cm column of mercury (NTP).

The ***elasticity*** of an object is the development of internal forces tending to return it to its initial form when it is distorted. Below the ***elastic limit,*** the ***elastic force*** of a spring displaced from its "free" position is

$$\text{Elastic force} = k \times \text{displacement}$$

where k is the ***elastic constant*** of the spring.

Some other mechanical properties of matter are ***malleability, ductility, tensile strength, hardness,*** and ***viscosity.***

New materials are continually advancing the technical aspect of our civilization.

The property ***thermal expansion*** is used in thermometry. The centigrade (C) thermometer scale is used in scientific work. For fixed points, the melting point of ice (at NP) is 0°C or 32°F, and the boiling point of water (at NP) is 100°C or 212°F. It follows that

$$\text{Degrees F} = \frac{9}{5}\,(\text{degrees C}) + 32,$$

or

$$\text{Degrees C} = \frac{5}{9}\,(\text{degrees F} - 32)$$

Linear thermal expansion is described:

$$\text{Change in length} = a \times \text{initial length} \times \text{change in temperature}$$

where a is ***the coefficient of linear expansion*** of the material.

Characteristic *melting points* and *boiling points* (at NP) and *thermal conductivities* are also important thermal properties of matter.

Optical properties of matter include the *reflection* and *transmission* of light which, when selective, account for characteristic *colors,* and *refraction,* which is so important in optical instruments.

An electrical property of matter, the ability to conduct electricity, is of inestimable value to us. The *electrical conductivities* of good conductors may be 10^{22} times those of insulators.

These physical properties of matter were selected to serve as a basis for further study.

QUESTIONS

1. Can all substances exist in all three states?
2. How do temperature and pressure determine the state of any given substance?
3. With what advantages have our accidental circumstances of temperature and pressure provided us?
4. Why does the scientist need exact definitions?
5. How are the basic units of the metric system defined?
6. What is the difference between mass and weight? The mass of the moon is 7.4×10^{22} kg. What would you say that its weight is?
7. How is density defined?
8. What would be the mass of a sphere of lead 15 cm in diameter?
9. Do all substances follow Hooke's law, $F = kx$?
10. If a mass of 4 kg stretches a spring 2 cm, how far would a mass of 16 kg stretch it? —if the spring were removed to twice its normal distance from the earth's center?
11. If a spring is stretched 10 cm by a force of 10 newtons and returns only 4 cm when the force is reduced to 5 newtons, what can be concluded about the elastic character of the spring?
12. Are properties such as elasticity, malleability, ductility, hardness, tensile strength, and viscosity found in all states of matter?
13. How does industrial progress depend on the mechanical properties of matter and upon the development of materials with special properties? What about Duralumin, stainless steel, rubber, Bakelite? What other special materials are needed today?
14. What centigrade temperatures correspond to 70°F (the temperature of a moderate day) and 120°F (the temperature of a very hot bath)?
15. If a 1-meter pendulum of a clock were made of copper, what would be its change in length when the temperature drops from 30°C to 10°C? The time for one swing of the pendulum is proportional to the square root of the length of the pendulum. Then, assuming that the clock keeps accurate time at 30°C, how much time would it gain during a day with the temperature at 10°C?
16. Why do large lakes freeze on the surface instead of the bottom? Of what importance is this?
17. Can we improve on thermal properties of materials found in nature? heat insulators?
18. Are the transparency, reflective power, and color of a material independent of one another?
19. Why might you expect electrical and thermal conductivities to be related?

CHAPTER V

ATOMS AND MOLECULES

The Idea of Elementary Substances. What is this stuff of which we and all our surroundings are made?

Curious man has always wondered about the composition of his environment. Aristotle decided that earth, air, fire, and water were the substances of which all materials are made, that is, that they were the ***elementary substances***. Although other classifications were suggested before and afterward, Aristotle's conclusions were accorded such great authority that they were almost universally accepted until the seventeenth century. On this basis the various kinds of matter were supposed to differ only in the relative amounts of the four elementary constituents.

Leucippus and Democritus proposed a quite different set of elements. They conceived matter as made of tiny indivisible units of elementary substances, ***atoms,*** and thought that substances differ only in the relative amounts and arrangements of these elementary particles. Although much like our modern view, their ideas were actually little more than hazy speculations. Certainly their conclusions had no experimental support and really had no greater justification than those of Aristotle. At a time of free speculation, it is not surprising that someone made a lucky guess which turned out to be partially correct.

The ancient alchemists who sought to transmute base metals into gold and silver performed some of the first chemical experiments, although usually not without attention to favorable astrological signs and mystical rites. Actually their efforts were encouraged by the Aristotelian point of view, for if all matter differed only in the proportion of four "substances," it should have been possible to separate the ultimate materials and recombine them into silver or gold, into the "elixir of life," or into the "philosopher's stone." Their search, of course, was fruitless because, as we know today, much more than a simple chemical

process is necessary to transmute one element to another. Nevertheless, the alchemists gradually developed many essential experimental procedures and learned much about the chemical properties of matter, thereby providing a background for modern chemistry.

(From the Bettmann Collection, courtesy of The Sky.)

Fig. 120. Alchemist in search for the secret of life.

Robert Boyle of Oxford (1627–1691) led the transition from alchemy to the science of chemistry. His careful experimental studies convinced him that a substance such as lead, mercury, or gold, regardless of the chemical and physical processes to which it is subjected, can always be brought back to its original state, and that it represents a true elementary substance which cannot be

decomposed. In *The Sceptical Chymist* he says: "I mean by elements certain primitive and simple or perfectly unmingled bodies; which, not being made of other bodies, or of one another, are the ingredients of which all those perfectly mixt bodies are compounded, and into which they can ultimately be resolved."

CHEMICAL ASPECTS OF MATTER

Physical and Chemical Phenomena. Why do we distinguish between physical and chemical phenomena? Should the physicist or the chemist study the conduction of electricity through metals? Through solutions? Through gases? Certainly the distinctions that have arisen are largely for convenience, and, as a glance through typical physics and chemistry texts will show, a great deal of overlapping naturally occurs. The chemist studies primarily the composition of matter and the changes in ***composition*** and ***energy*** that take place during the decomposition and the formation of substances. In studying gross physical properties of matter, such as we discussed in the last chapter, the physicist has gradually been led to investigate atoms and molecules, that is, the detailed structure of matter. Since the ultimate structure of matter must be known in order to interpret chemical changes, its study actually belongs as much to chemistry as to physics. This fact helps us to see that these two fields are so closely related that the thorough knowledge of one necessarily includes much of the other.

Elements, Compounds, and Mixtures. How do we know whether a given specimen of material is an ***element,*** a ***compound,*** or a ***mixture?*** Boyle's definition of an element is essentially correct, for if we cannot further decompose the substance by ordinary physical and chemical processes we classify it as an ***element.*** And a ***compound*** is just a ***chemical combination*** of two or more elements.

How are we, then, to distinguish between a compound and a simple physical mixture of two elements? An easy experiment will illustrate the distinction. Let us use some iron filings and some powdered sulfur (with chemical symbols Fe and S respectively). Both are elements, and they differ in their chemical and physical properties. The iron is dark gray in color, the sulfur yellow. The iron dust is attracted to a magnet, the sulfur is not. The sulfur dissolves in carbon disulfide (CS_2), but the iron is not influenced. However, the iron is attacked by hydrochloric acid (HCl) and an

odorless, highly inflammable gas, hydrogen, is given off, while the sulfur is unaffected.

Suppose that we thoroughly mix the sulfur and iron. We thus obtain a yellowish-gray powder which is a ***physical mixture*** and

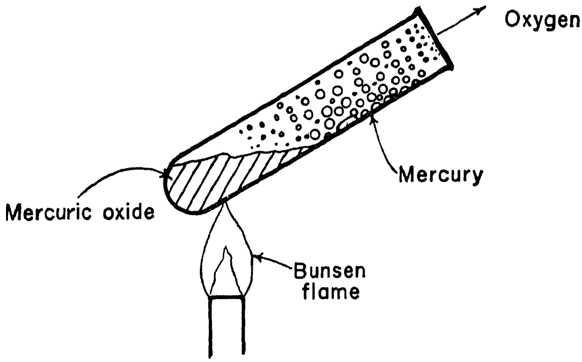


Fig. 121. Mercuric oxide, when heated, decomposes into mercury and oxygen.

not a ***compound.*** The iron can be separated readily from the sulfur with the magnet, and the carbon disulfide and hydrochloric acid operate on each constituent as though the other were not present. Both iron and sulfur retain their identity and their original properties.

Synthesis. If, however, this mixture is placed in a test tube and heated over a Bunsen flame, the mixture quickly glows dull red, and after cooling a great change in its properties may be noticed. The material is now black in color, unattracted by the magnet, and insoluble in carbon disulfide.[1] When hydrochloric acid is added, a foul-smelling gas (hydrogen sulfide) is given off. The new substance formed by ***synthesis*** is, therefore, a compound, a combination of the two original substances which possesses entirely different chemical and physical properties than its constituents. This new compound is called ferrous sulfide. The chemist expresses the formation of ferrous sulfide (FeS) from iron (Fe) and sulfur (S) by the symbolism:

$$Fe + S \rightarrow FeS$$

Decomposition. The type of reaction that is the opposite of synthesis is ***decomposition,*** the breaking down of one substance

[1] If the proportions were not correct there would be an excess of iron or sulfur which would still possess its original properties. See p. 184 on the law of definite proportions.

into two or more substances generally with quite different properties. If red oxide of mercury (mercuric oxide) is heated vigorously in a test tube, a gas is liberated which will cause a glowing splinter placed in the test tube to burst into flame. This action shows that the gas is oxygen. Simultaneously, tiny droplets which obviously are metallic mercury condense on the cool upper walls of the test tube. Thus it is clear that at least two new substances are formed, in other words, that the one original substance is ***decomposed.***

Chemical Properties. Just as elasticity, color, electrical conductivity, etc., are physical properties, tendencies to react chemically with other substances are characteristic chemical properties. For example, does the substance react with various acids or bases; does it combine with oxygen in rapid combustion, slowly, or not at all; is it soluble in water, alcohol, or any other liquid?

Some chemical reactions give off energy—these are called ***exothermic.*** In others energy is absorbed, and these are called ***endothermic.***

After Boyle's experiments, the development of chemistry progressed slowly. For a long period, a controversy raged over the nature of combustion. Stahl (1660–1734), a German professor of medicine, put forth a theory that combustion of a body was due to the escape from it of something called "phlogiston." Coal, alcohol, wood, etc., were thought to be combinations of phlogiston with the ash of the material. This was doubtless the revival of an exceedingly old idea which may have been suggested by the smoke rising from fires. The discovery of ***hydrogen*** gas by Cavendish in 1750, and the discovery in 1774 by Priestley and Scheele of the gas ***oxygen*** which composes one-fifth of the atmosphere were at first supposed to support the "phlogiston" theory. Shortly afterward, however, ***Antoine Lavoisier's*** careful investigations involving these gases led to the upset of the "phlogiston" idea. Lavoisier (1743–1794) was the great French chemist who laid the basis for modern chemistry. His careful quantitative experiments showed that the combination of a substance with oxygen and not the escape of "phlogiston" was the real explanation of combustion. This was an important step toward understanding the nature of chemical processes.

Conservation of Matter. Lavoisier's work led him to a most fundamental conclusion: ***In every chemical process the quantity of matter, that is, the mass, remains constant; only the form changes.***

In other words, the total mass of substances which react chemically is equal to the mass of the resulting products. This says that matter can neither be created nor destroyed. In recent years physicists have been forced to amend this statement,[1] but for ordinary

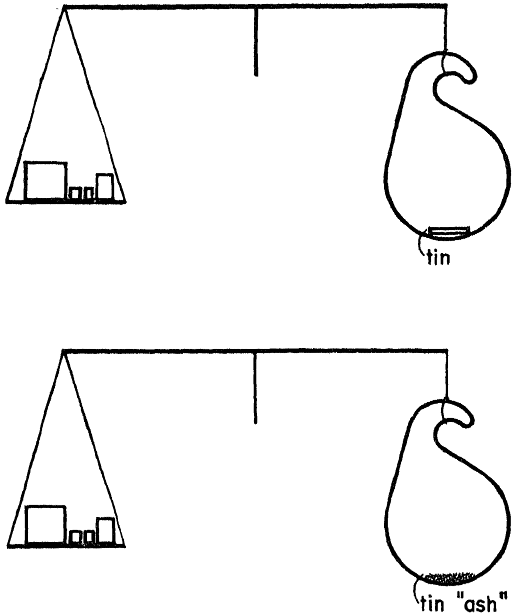


Fig. 122. Lavoisier showed that a closed glass vessel containing tin and air (above) did not change weight when the tin was "burned" by sunlight concentrated with a large lens. He noticed that air rushed in when the container was cracked after the experiment.

chemical and physical processes it holds accurately. Lavoisier had demonstrated his conclusion strikingly by "burning" tin and lead in a closed glass vessel and showing that the weights, before and after, were exactly the same. Thus the phlogiston theory was completely exploded.

The Elements. The work of Lavoisier and the researches of many chemists and physicists since have shown that the vast variety of substances in the universe are formed from only 93 or 94 basic elements. Of these, some 88 have definitely been found in natural substances. A few elements, such as iron and copper, have been known since antiquity. Others are so rare that they have

[1] See Chap. XXI on equivalence of mass and energy.

been found only recently by most refined methods. Several have been identified only in products of "atom smashing."[1] About 20 elements such as gold, platinum, silver, copper, nitrogen, and helium react so slowly with oxygen and other substances that they are

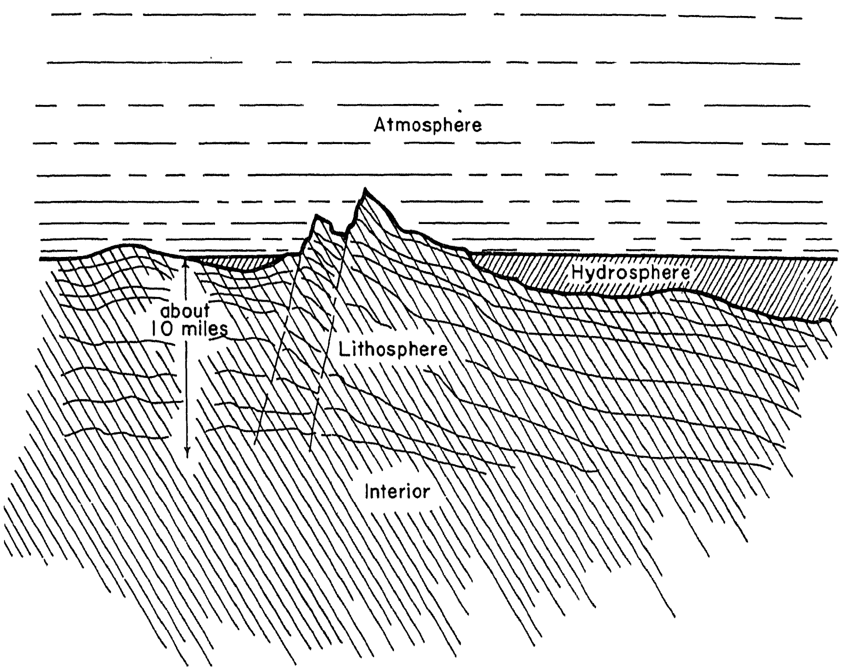


Fig. 123. Atmosphere, hydrosphere, lithosphere.

sometimes found free (that is, in an uncombined form) in nature. Most elements occur naturally only in compounds, of which hundreds of thousands are known to exist. Many other compounds may be produced synthetically. The methods for refining and alloying iron, copper, tin, aluminum, and others of the metals and minerals which we use today resulted from a long period of chemical, physical, and metallurgical research.

Our Raw Materials. In the last analysis we know of just 89 fundamental assets with which to work on this planet, the 88 or so natural elements which occur in, on, and over the earth, and the radiant energy which comes to us largely from the sun. From these we must construct the material aspects of the civilization of the future.

[1] See Chap. XXI on nuclear transmutation or "atom smashing."

APPROXIMATE COMPOSITION OF LITHOSPHERE*

Element	Percentage by weight	Element	Percentage by weight
Oxygen	46.7	Hafnium	0.003
Silicon	27.7	Thorium	0.002
Aluminum	8.1	Lead	0.002
Iron	5.0	Cobalt	0.001
Calcium	3.7	Boron	0.001
Sodium	2.7	Beryllium	0.001
Potassium	2.6	Molybdenum	? × 10^{-4}
Magnesium	2.1	Rubidium	? × 10^{-4}
Titanium	0.62	Arsenic	? × 10^{-4}
Hydrogen	0.14	Tin	? × 10^{-4}
		Bromine	? × 10^{-4}
Phosphorus	0.13	Cesium	? × 10^{-5}
Carbon	0.09	Scandium	? × 10^{-5}
Manganese	0.09	Antimony	? × 10^{-5}
Sulfur	0.05	Cadmium	? × 10^{-5}
Barium	0.05	Mercury	? × 10^{-5}
Chlorine	0.04	Iodine	? × 10^{-5}
Chromium	0.03	Bismuth	? × 10^{-6}
Fluorine	0.03	Silver	? × 10^{-6}
Zirconium	0.02	Selenium	? × 10^{-6}
Nickel	0.02	Platinum	? × 10^{-7}
Strontium	0.02	Tellurium	? × 10^{-7}
Vanadium	0.02	Gold	? × 10^{-7}
Cerium, Yttrium	0.01	Iridium	? × 10^{-8}
Copper	0.01	Osmium	? × 10^{-8}
Uranium	0.008	Indium	? × 10^{-8}
Tungsten	0.005	Gallium	? × 10^{-8}
Lithium	0.004	Thallium	? × 10^{-8}
Zinc	0.004	Rhodium	? × 10^{-8}
Columbium, Tantalum	0.003	Palladium	? × 10^{-8}
		Ruthenium	? × 10^{-8}
		Germanium	? × 10^{-8}
		Radium	? × 10^{-10}

* After Clarke and Stephens, *U. S. Geological Survey Professional Paper* 127 (1924).

Usually we consider the supply of elements as from three possible sources:

1. The ***lithosphere,*** or solid crust of the earth about 10 miles thick, of about 3×10^{22} kg mass;

2. The ***hydrosphere,*** or liquid layer, of about 1.5×10^{21} kg; and

3. The *atmosphere,* or gaseous layer of about 5×10^{18} kg.

The solid crust has not been completely investigated, for sampling has been limited to outcroppings and to mines and wells, the deepest of which is only about 3 miles. Nevertheless, geologists have accumulated enough information to form a fairly reliable estimate of the content of this crust.

The composition of the earth below the crust is still somewhat speculative, but there is evidence that the outer layers are largely of igneous rocks rich in silica. Because the earth is probably like other bodies in the solar system, of which meteorites are supposed to be typical, it is believed to become richer in metals such as iron and nickel as the center is approached. It is doubtful if these materials will ever be available for practical use.

The largest fraction of the hydrosphere is sea water. Millions of years of washing the earth's surface by rain and tide have brought samples of all of the elements into solution in the sea. Including the hydrogen and oxygen that are combined to make up the water (H_2O), the most abundant elements found in sea water are shown in the following table.

MOST ABUNDANT ELEMENTS IN THE HYDROSPHERE*

Element	Percentage by weight	Element	Percentage by weight
Oxygen	85.79	Sulfur	0.09
Hydrogen	10.67	Calcium	0.05
Chlorine	2.07	Potassium	0.04
Sodium	1.14	Bromine	0.008
Magnesium	0.14	Carbon	0.002

* After Clarke and Stephens, *U. S. Geological Survey Professional Paper* 127 (1924).

The elements not included in this table are present in exceedingly small quantities. Man has not yet utilized this great reservoir of raw materials to any significant extent, although installations for the extraction of bromine from sea water are now functioning and others are planned. Even gold has been extracted as a by-product in the bromine concentration plants.

The atmosphere is exceedingly important to both plant and animal life. Animals inhale oxygen and exhale carbon dioxide. Plant life, in its living process, takes in carbon dioxide and gives off oxygen. The balance between these processes is in general well maintained.

GASEOUS COMPOSITION OF DRY AIR AT SEA LEVEL*

Element	Percentage by weight	Element	Percentage by weight
Nitrogen	78.03	Neon	0.0012
Oxygen	20.99	Helium	0.0004
Argon	0.94	Krypton	0.00005
Carbon dioxide	0.03	Xenon	0.000006
Hydrogen	0.01		

* After Humphreys, *International Critical Tables*, Vol. 1, p. 393, McGraw-Hill Book Company, Inc., New York, 1926.

The so-called ***rare gases,*** argon, helium, neon, krypton, and xenon, make up nearly one per cent of the air's mass.

Geologists, chemists, and biologists are clearly concerned with many aspects of the composition of our earth and its atmosphere that cannot be included in this hasty inventory of the amounts and kinds of matter that we have available as our working materials. We shall concentrate instead upon the results of inquiries of the physicist and chemist into the nature of these materials.

THE ATOMIC NATURE OF MATTER

The path to the general acceptance of the atomic nature of matter was long and indirect. The final step was assured by John Dalton, the English chemist, in 1808, when he published two fundamental conclusions from his work.

Law of Definite Proportions. ***All elements combine chemically in definite proportions of mass.***[1] The proportions in many cases can be expressed closely by whole numbers. Dalton found that when hydrogen unites with oxygen to form water the proportion (by mass) is always the same, the accepted values being 1 part of hydrogen to 8 parts of oxygen. In the experiment in which we combined iron and sulfur (page 177), the union of the constituents is complete only if the masses of iron and sulfur have the proper ratio. If 56 g of iron and 32 g of sulfur are used, 88 g of ferrous sulfide (FeS) result. If a different proportion is used, an excess of one or the other element remains. Similarly, when compounds are decomposed the masses of the decomposition products always have a fixed ratio to each other.[1] For example, 216 g of mercuric oxide (HgO) yields 200 g of mercury and 16 g of oxygen.

[1] Except in cases of differing isotopic proportion; see Chap. XX on isotopes.

Law of Multiple Proportions. Sometimes the same elements can be combined to form two or more entirely different compounds, depending on the conditions under which union takes place. When this happens, the ratio of the masses of two elements in one compound is to the corresponding ratio for the same two elements in another compound as one small whole number is to another. Carbon and oxygen may combine to form carbon monoxide (CO), a colorless and odorless but very poisonous gas (responsible for deaths in closed garages from automobile "exhaust," in houses from leaky furnace flues, etc.). Carbon and oxygen also combine to form the harmless carbon dioxide (CO_2) (which our lungs produce during the breathing process). The ratio of the mass of oxygen to that of carbon in carbon monoxide is 16:12 and in carbon dioxide 32:12. Thus, the ratio of the mass of oxygen per gram of carbon in carbon dioxide to the corresponding quantity for carbon monoxide is (32:12)/(16:12) = 2:1.

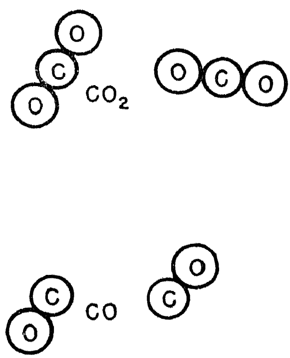


Fig. 124. Schematic representation of O and C atoms united to form CO_2 and CO molecules.

Dalton saw the following implication in his "law" of definite proportions: If the proportions in a compound are always the same, it should, for example, be possible that with the simplest type of compound the quantity can be made smaller and smaller until finally there remains one elementary unit of one element united to one elementary unit of the other. Thus, the compound would be made up of identical "blocks" consisting of one unit of each element. Then, regardless of the number of "blocks" piled together, the proportions of the two elements included cannot be different from their proportions in each "block," that is, they are just the relative masses of the two elementary units.

The law of definite proportions ***suggested*** that there is an indivisible unit of each element. The law of multiple proportions supported this idea, because this law follows directly if different compounds of the same elements are made up of "blocks" which differ only in the number of units of each element that they contain. For example, a unit of one element could be combined with either one, two, or three units of another element.

Through such reasoning, Dalton concluded that ***all elements must be made of ultimate units*** which he called ***atoms*** in recognition of the old ideas of Democritus and Leucippus.

Atoms and Molecules. Atoms then combine in the formation of compounds. A modern chemical formula such as CO_2 simply means that one atom of carbon, C, is combined with two atoms of oxygen, O, to form that smallest entity of what is known as carbon dioxide. That smallest stable entity of any element or compound we call a ***molecule.*** Usually it consists of two or more atoms. For example, gaseous hydrogen, nitrogen, and oxygen normally exist as diatomic molecules, that is, two atoms joined together (H_2, N_2, O_2). In spite of the simplicity of this idea, it was not generally accepted for a long time. Many controversies delayed important generalizations such as the atomic theory, which were needed to suggest the powerful methods of present-day chemistry.

Two other outstanding steps in the development of the atomic theory deserve mention in our brief survey. On the basis of the experiments initiated by Dalton, which showed that hydrogen and oxygen combine in a 1:8 mass ratio, it was proposed that 1 and 8 be used as the ***atomic weights*** of hydrogen and oxygen, that is, the arbitrary relative weights of the atoms of hydrogen and oxygen. This was done in the belief that the water molecule was HO. However, Gay-Lussac, famed for his work on gases, showed in 1808 that ***two volumes of hydrogen*** combine with ***one volume of oxygen*** to make ***two volumes of water vapor.*** Gay-Lussac proposed 16 as the atomic weight of oxygen, and advanced the hypothesis that under like conditions of pressure and temperature equal volumes of gases contain the same number of atoms. But he could not explain why two volumes of water vapor should be formed.

Finally in 1811 the Italian physicist Avogadro explained Gay-Lussac's difficulty. He suggested that the elementary unit of hydrogen gas, the ***molecule of hydrogen gas,*** is composed of two hydrogen atoms, and the molecule of oxygen of two oxygen atoms. He then proposed the famous law which bears his name. Equal volumes of ***any gases*** (under the same conditions) ***contain the same number of molecules.*** On this basis the explanation of the volume relations in the formation of water is very simple. Water has the formula H_2O, indicating that its molecule consists of two atoms of hydrogen and one of oxygen. Since equal volumes of

gases contain equal numbers of ***molecules*** (not atoms), ***two volumes*** of hydrogen will combine with ***one volume*** of oxygen to form ***two volumes*** of H_2O, for each oxygen molecule can split up into two oxygen atoms and each of these atoms can attach itself

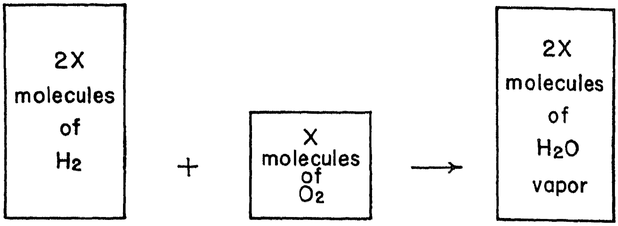


Fig. 125. Two volumes of hydrogen gas unite with one volume of oxygen gas to form two volumes of water vapor.

to a hydrogen molecule to make a water molecule. In this way, Avogadro's hypothesis, with observations such as Dalton began, made it possible to determine the relative atomic weights of all elements which may be studied as gases or which combine with gases.

The atomic theory has finally been accepted by all chemists and physicists, although even as late as 1900 many reputable scientists opposed it. Numerous types of experiments have now demonstrated:

1. That all elements are composed of exceedingly small discrete particles, or atoms, which cannot be divided further without losing the chemical and physical characteristics of the element;

2. That there are 93 or 94 major types of atoms (and thus 93 or 94 elements) present in matter,[1] each of which has a characteristic average weight;

3. That all the matter in the universe is made of molecules, each of which is composed of atoms (or an atom) of one or more elements.

Periodic Table of Elements. Even while many of the elements were still undiscovered, several men, among them Mendeléeff and Lothar Meyer, had observed interesting regularities in the proper-

[1] There is good evidence that elements of atomic number 43, 61, 85, 87, 93, and possibly 94, not definitely found in nature, have been produced artificially (see p. 191 on atomic number and Chap. XXI on artificial production of elements). It is possible that some elements will be formed with atomic number greater than 94, the present limit.

PROPERTIES OF THE ELEMENTS

Atomic number	Element		Nature (if gas or liquid, at 20°C)
	Symbol	Name	
1	H	Hydrogen	Gas; in water, acids, bases and organic compounds
2	He	Helium	Rare gas; inert, no compounds
3	Li	Lithium	Alkali metal; soft; readily combustible
4	Be	Beryllium	Metal; hard; forms strong, resistant alloys
5	B	Boron	In boric acid and borax
6	C	Carbon	Half-million compounds known, in all organic compounds
7	N	Nitrogen	Gas; 78 per cent of atmosphere; relatively inert; in all living things
8	O	Oxygen	Gas; 21 per cent of atmosphere; combines with almost all elements; most abundant element
9	F	Fluorine	Halogen gas; very active
10	Ne	Neon	Rare gas; inert, no compounds
11	Na	Sodium	Alkali metal; soft; readily combustible
12	Mg	Magnesium	Metal; fairly tough; readily combustible
13	Al	Aluminum	Metal; in clays; useful for light-weight construction
14	Si	Silicon	In many minerals; second most abundant element
15	P	Phosphorus	Yellow, red, and black forms; in protoplasm, nerve tissue, and bones
16	S	Sulfur	Free in nature; in many salts
17	Cl	Chlorine	Halogen gas; active; in many salts
18	A	Argon	Rare gas; inert, no compounds; 1 per cent of atmosphere
19	K	Potassium	Alkali metal; soft; readily combustible; radioactive
20	Ca	Calcium	Alkali earth metal; readily combustible; in bones, teeth, shells, etc.
21	Sc	Scandium	Rare earth metal
22	Ti	Titanium	Metal; strengthens steel
23	V	Vanadium	Metal; hardens steel
24	Cr	Chromium	Metal; hardens steel, makes it stainless; used for plating
25	Mn	Manganese	Metal; used in Fe, Cu, and Ni alloys
26	Fe	Iron	Metal, cheapest; magnetic; widely cast and used in steel (1 to 2 per cent C)
27	Co	Cobalt	Metal; magnetic; used in alloys
28	Ni	Nickel	Metal; magnetic; used in alloys and for plating
29	Cu	Copper	Metal, reddish; free in nature; used in brass and bronze and for electrical conductors

PROPERTIES OF THE ELEMENTS.—(Continued)

Atomic number	Element		Nature (if gas or liquid, at 20°C)
	Symbol	Name	
30	Zn	Zinc	Metal; used for plating
31	Ga	Gallium	Metal; melts 30°C
32	Ge	Germanium	Metal
33	As	Arsenic	In many poison compounds
34	Se	Selenium	Used in ceramics and photocells
35	Br	Bromine	Halogen liquid; compounds used in photography
36	Kr	Krypton	Rare gas; inert, no compounds
37	Rb	Rubidium	Alkali metal; soft; radioactive
38	Sr	Strontium	Alkali earth metal; salts redden flames
39	Y	Yttrium	Rare earth metal
40	Zr	Zirconium	Metal; oxide used as gems, in paints
41	Cb	Columbium	Metal
42	Mo	Molybdenum	Metal; hard; used in tool steel, vacuum tube elements
43	Ma	Masurium	Natural existence doubtful; produced artificially
44	Ru	Ruthenium	Metal; free in nature; similar to Pt
45	Rh	Rhodium	Metal; free in nature; similar to Pt
46	Pd	Palladium	Metal; free in nature; similar to Pt
47	Ag	Silver (argentum)	Metal; free in nature; best thermal and electrical conductor
48	Cd	Cadmium	Metal; used for plating
49	In	Indium	Metal; used for plating
50	Sn	Tin (stannite)	Metal; used for plating
51	Sb	Antimony (stibium)	Metal; rarely free in nature; used in type alloys, etc.
52	Te	Tellurium	Grayish powder; used in ceramics
53	I	Iodine	Halogen, least active; in seaweed
54	Xe	Xenon	Rare gas; inert, no compounds
55	Cs	Cesium	Alkali metal; used in photocells and as vacuum "getter"
56	Ba	Barium	Alkali earth metal
57	La	Lanthanum	Rare earth metal
58	Ce	Cerium	Rare earth metal
59	Pr	Praseodymium	Rare earth metal
60	Nd	Neodymium	Rare earth metal
61	Il	Illinium	Natural existence questionable; artificially produced
62	Sa	Samarium	Rare earth metal
63	Eu	Europium	Rare earth metal } very similar
64	Gd	Gadolinium	Rare earth metal } very similar
65	Tb	Terbium	Rare earth metal } very similar

PROPERTIES OF THE ELEMENTS.—(Continued)

Atomic number	Element: Symbol	Element: Name	Nature (if gas or liquid, at 20°C)
66	Ds	Dysprosium	Rare earth metal (very similar)
67	Ho	Holmium	Rare earth metal (very similar)
68	Er	Erbium	Rare earth metal (very similar)
69	Tm	Thulium	Rare earth metal (very similar)
70	Yb	Ytterbium	Rare earth metal
71	Lu	Lutecium	Rare earth metal
72	Hf	Hafnium	Metal
73	Ta	Tantalum	Metal; used for filaments and in steels
74	W	Tungsten (wolfriam)	Metal; used for lamp filaments; hardens steel
75	Re	Rhenium	Metal
76	Os	Osmium	Metal; hard; densest element
77	Ir	Iridium	Metal; free in nature; similar to Pt; used with Os on pen tips
78	Pt	Platinum	Metal; free in nature; used as catalyst and for jewelry
79	Au	Gold (aurum)	Metal, most malleable; free in nature; used for coinage, jewelry
80	Hg	Mercury (hydrargyrum)	Liquid; metal; rarely free in nature; forms amalgams with metals
81	Tl	Thallium	Metal; similar to Pb; forms poisonous salts
82	Pb	Lead (plumbum)	Metal; ductile; used in low-melting-point alloys; end of radioactive series
83	Bi	Bismuth	Metal; free in nature; similar to Pb; used in type metal
84	Po	Polonium (radium F)	Radioactive; metal
85	....	....	Not found in nature; artificially produced; radioactive
86	Rn	Radon	Radioactive; rare gas; densest gaseous element; used in therapy
87	....	....	Not found in nature; artificially produced; radioactive
88	Ra	Radium	Radioactive; metal; used in luminous paint
89	Ac	Actinium	Radioactive; metal
90	Th	Thorium	Radioactive; metal
91	Pa	Protoactinium	Radioactive; metal
92	U	Uranium	Radioactive; metal; used in fluorescent glass
93	....	Neptunium (?)	Not found in nature; produced artificially; radioactive
94	....	....	Not found in nature; possibly produced artificially (?)

ties of those elements which were known. It was found that when the elements were arranged in order of ascending ***atomic weight,*** similar sequences of physical and chemical characteristics recurred

more or less regularly throughout this series of elements. For example, if we plot the density of the various solid elements against atomic weight (Fig. 126), we see that the density increases and decreases in fairly definite intervals. Observations similar to this

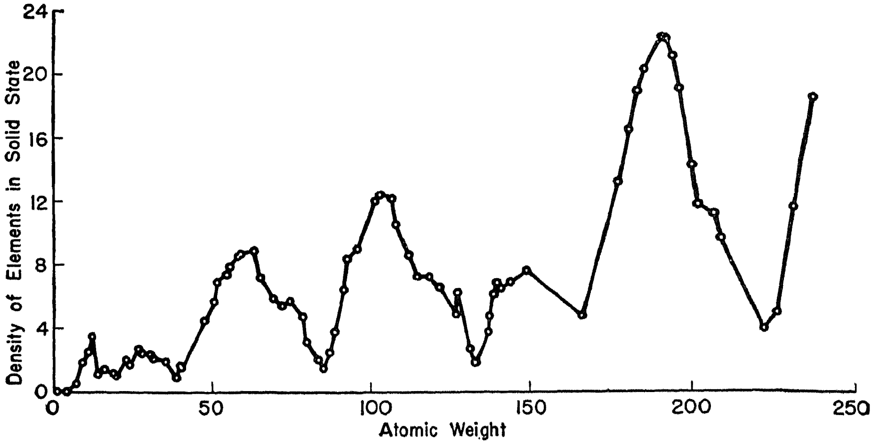


Fig. 126. Density of solid elements varies almost "periodically" with atomic weight.

led to arranging the elements in a so-called ***periodic table,*** such as the one in the table on page 192.

Atomic Number. The elements are numbered from left to right in the periodic table in order of increasing atomic weight. As we shall see in the latter chapters of this book, this numbering has much more significance than was at first realized.

Atomic Weight. The discoveries of Dalton and his contemporaries yielded only ratios of the weights of various atoms. To establish a definite scale of atomic weight, that of oxygen is arbitrarily taken to be exactly 16.0000. Many of the atomic weights of the elements are nearly, but not exactly, whole numbers.

Solids Have Structure. Even the casual observer notices that most solid materials have characteristic types of structure known as crystal forms. Ordinary table salt tends to crystallize as cubes (Fig. 128), a sugar crystal is more complex in that the angles between its faces are not all 90 deg, and quartz is often found in the form of a hexagonal prism, frequently with tapered caps on the two ends. Snowflakes or frost crystals are six-sided. Each kind of precious gem has its natural geometry. As is well known to gem cutters, all crystals split comparatively readily along planes that are parallel to the natural surfaces. What could give rise to these

PERIODIC TABLE OF THE ELEMENTS

Scheme:*

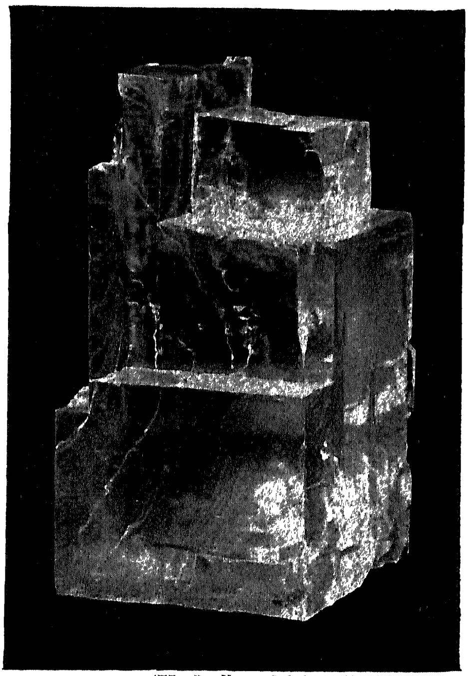
Atomic No. Symbol Atomic weight

O	I	II	III		IVa	Va	VIa	VIIa	VIIIa			Ia	IIa	IIIa	IV	V	VI	VII
	1 H 1.008																	
2 He 4.002	3 Li 6.94	4 Be 9.02	5 B 10.82												6 C 12.00	7 N 14.01	8 O 16.000	9 F 19.00
10 Ne 20.18	11 Na 23.00	12 Mg 24.32	13 Al 26.97												14 Si 28.06	15 P 31.02	16 S 32.06	17 Cl 35.46
18 A 39.94	19 K 39.10	20 Ca 40.08	21 Sc 45.10		22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.84	27 Co 58.94	28 Ni 58.69	29 Cu 63.57	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.93	34 Se 79.2	35 Br 79.92
36 Kr 82.9	37 Rb 85.4	38 Sr 87.6	39 Y 88.9		40 Zr 91.2	41 Cb 93.3	42 Mo 96.0	43 Ma ?	44 Ru 101.7	45 Rh 102.9	46 Pd 106.7	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.5	53 I 126.9
54 Xe 130.2	55 Cs 132.8	56 Ba 137.4	57 La 138.9	58–71 Rare earths	72 Hf 178.6	73 Ta 181.4	74 W 184.0	75 Re 186.3	76 Os 190.8	77 Ir 193.1	78 Pt 195.2	79 Au 197.2	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 210.0	85
86 Rn 222	87	88 Ra 226.0	89 Ac 227		90 Th 232.1	91 Pa 231	92 U 238.1	93 ?										

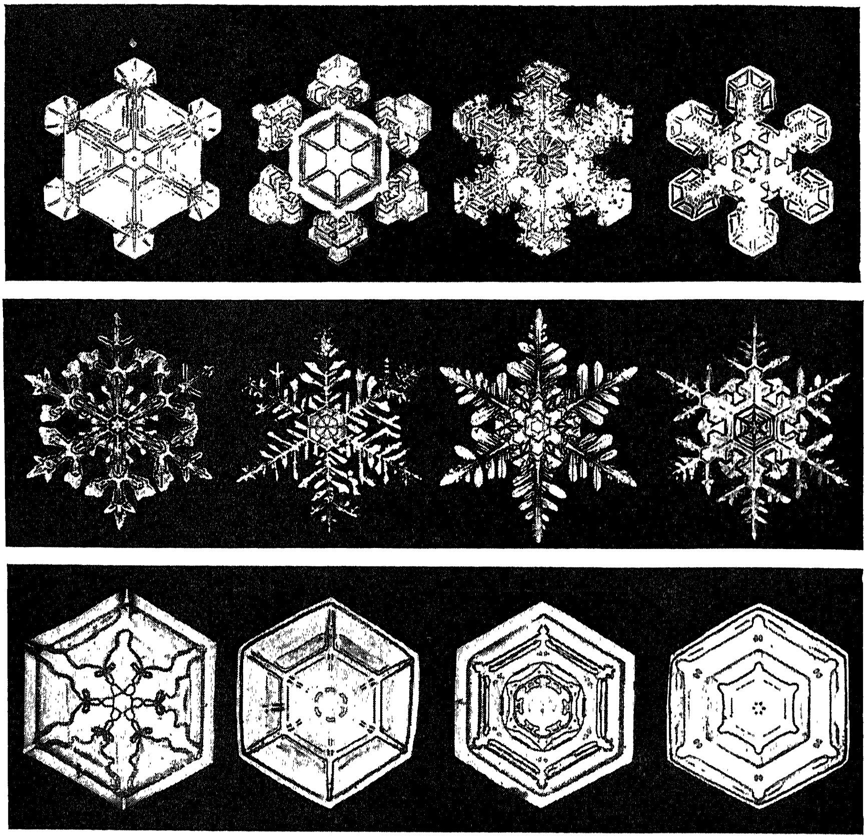
In general, the properties of the elements in each vertical column are similar.

* For names of the elements see the table on pp. 188–190.

(*American Museum of Natural History.*)
Fig. 127. Smoky quartz crystals.



(*Ward's Natural Science Establishment.*)
Fig. 128. Rock-salt crystal showing cubic cleavages.



(U.S. Weather Bureau.)

Fig. 129. Microphotographs of snow crystals. Selected from thousands of photographs by W. A. Bentley.

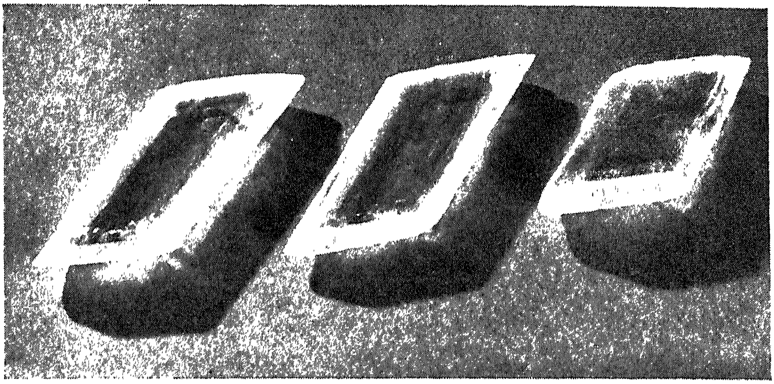
characteristic forms and special surfaces unless an orderly "stacking" of similar elementary units—that is, atoms?

Microscopic, X-ray, and neutron[1] observations have shown that virtually all solids and indeed some liquids have such a structural organization. Mechanical properties, including strength, elasticity, hardness and ductility, thermal properties, and even optical, magnetic, and electrical properties of materials depend greatly on their crystalline nature.

Studies of crystal structure and crystallization are very important in biological as well as physical sciences. They are especially useful in the field of metallurgy and for the identification of

[1] See Chap. XIX on X rays and Chap. XXI on neutrons.

minerals. Crystallization processes are often used in the purification of substances. In fact, the production of a crystal is frequently taken as a criterion of purity, and this is applied to the purification of complicated substances such as hormones and vitamins.



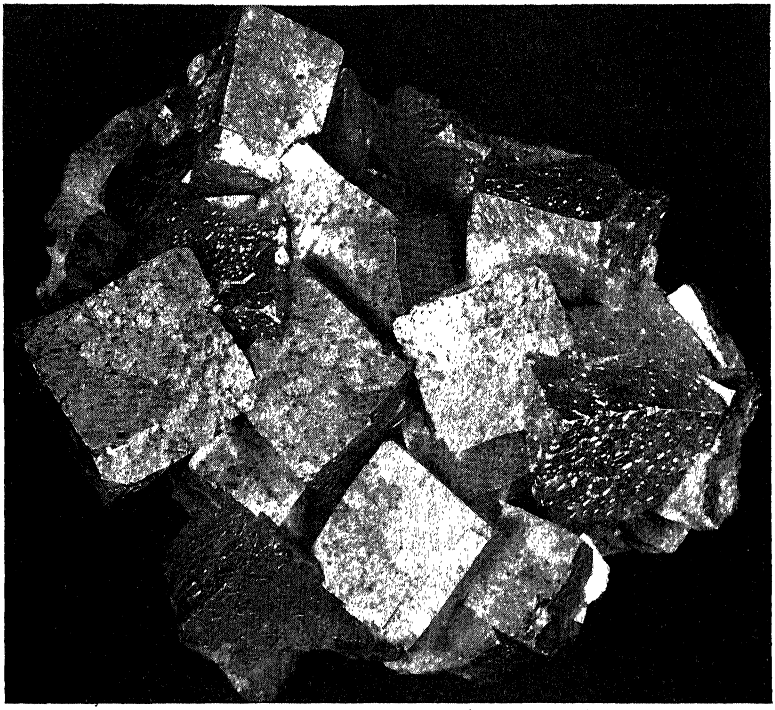
(Ward's Natural Science Establishment.)

Fig. 130. Gypsum crystals.

How Do We Know There Are Atoms? The work of Dalton, Gay-Lussac, and Avogadro seems very convincing, but after all no one has seen a single atom, and probably no one ever will.

We cannot include here a complete discussion of all the experiments that indicate the existence of atoms, but as we go along we shall have more and more evidence supporting the atomic theory. For example, the formation of a crystal is difficult to understand unless the substance is assumed to be composed of similar units (molecules or atoms) which pack together to form the characteristic structure. Among other phenomena that can be interpreted most simply in terms of the atomic theory are the exertion of pressure by gases, the conduction of electricity, the emission of characteristic spectra by elements, and the photoelectric effect.

Effects of Single Atoms. The most direct indication of the existance of atoms has come recently as the result of the discovery of radioactivity. Becquerel discovered radioactivity in 1896, and subsequently his work was enlarged by the Curies, Debierne, Rutherford, and many others. The atoms of elements of highest atomic weight, from uranium to lead, are unstable and from time to time break up, emitting several types of fragments. One type, the so-called alpha particle, has been shown by spectroscopic tests to be the interior of a helium atom. These stripped helium atoms



(*Ward's Natural Science Establishment.*)

Fig. 131. Cubic crystals of galena.

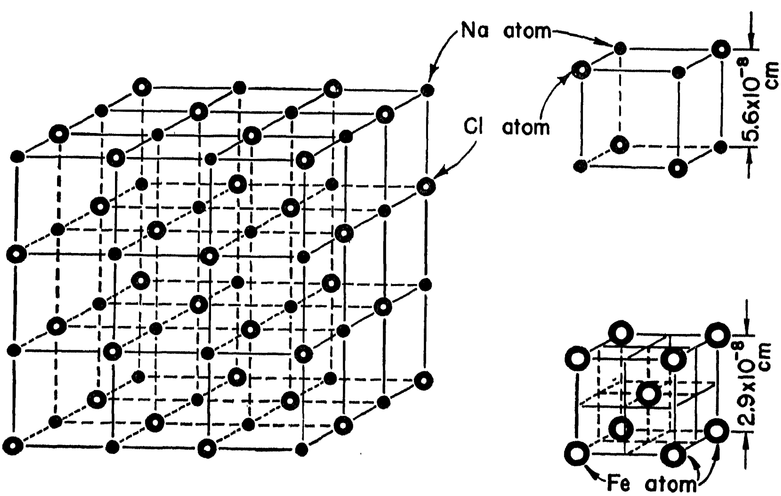
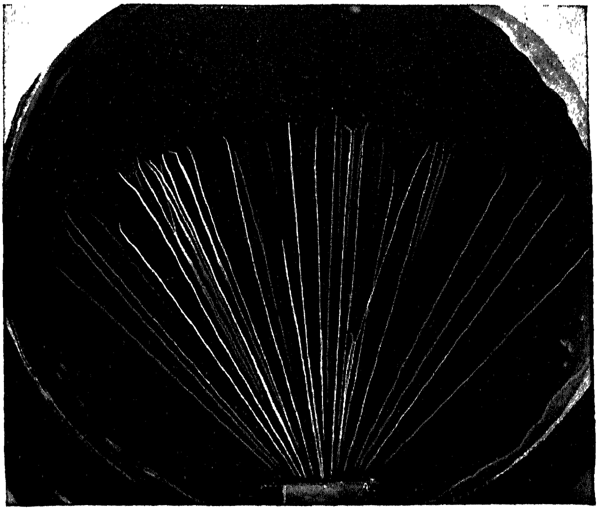


Fig. 132. Arrangement of sodium and chlorine atoms in a crystal of table salt (left). Unit cube of sodium chloride crystal (upper right) and of iron crystal with atom at center (lower right).

are ejected with speeds up to 15,000 miles per second, and because of this enormous speed their effects can be detected directly in several ways. When they are allowed to strike fluorescent materials such as zinc sulfide, tiny scintillations can be seen with a micro-



(Reproduced from Rasetti, "Elements of Nuclear Physics," Prentice-Hall, Inc., by permission of publishers.)

Fig. 133. Paths of single high-speed atoms (stripped helium atoms) made visible in cloud chamber.

scope. These faint bursts of light occur each time an alpha particle hits a zinc sulfide crystal and disrupts it. Watch dials are made luminous by mixtures of radioactive materials and zinc sulfide; the cumulative effect of many individual flashes of light is a continuous illumination.

There are two other major methods for detecting single alpha particles. When one of these high-speed "projectiles" rips through the air in an enclosure, it partially disrupts nitrogen and oxygen atoms along its path, leaving a trail of electrified particles. These electrically charged particles, or ***ions,*** can be made to produce a tiny electrical discharge which can be amplified to give a sharp click in a loudspeaker each time an alpha particle passes through the enclosure. Such a detecting device is commonly called a ***Geiger counter.***

The ***Wilson cloud chamber*** gives a still more vivid effect from a single high-speed alpha particle. The apparatus is arranged so that conditions in a chamber favor the formation of a fog of water

droplets. When an alpha particle enters the chamber, the water droplets condense preferentially on the ions produced by the passage of the particle through air. As a result, a trail of tiny droplets is formed along its path. Such cloud tracks produced by high-speed charged particles can be seen easily and even photographed.

Thus the *effects* of single atomic particles can be seen, heard, and recorded electrically. We do not see the atoms themselves, ***only their effects.*** Like much scientific reasoning, the demonstration of the existence of atoms depends on a long chain of evidence, but it is evidence that can hardly be doubted.

Inside the Atom. In the past 40 years the physicist has been probing deeper and deeper into the internal secrets of the atom itself. Originally supposed to be a hard little sphere of the elementary material, we now know that each atom is almost empty space. Crudely speaking, it is much like our solar system, with a positively charged heavy central "sun," or ***nucleus,*** which has most of the mass, surrounded by so-called "planetary" ***electrons*** which are negative electrical charges. The atoms of each element have a characteristic internal structure. The search for knowledge of the interior of the atom and even of its central "sun" makes a fascinating story which will unfold as we continue.

For the present, we need not inquire further into the internal nature of the atom, because for most of our immediate purposes the atom itself can be considered to be the structural unit. We shall make full use of the concept that all matter is composed of atoms, and that all physical, chemical, and biological phenomena must depend ultimately on the characteristics of these atoms or the molecules which they form.

FOR STUDY AND READING

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SUMMARY

Robert Boyle (1627–1691) introduced our modern idea of elements. An ***element*** cannot be decomposed by ordinary physical

and chemical methods. In a ***mixture*** of two elements the original characteristics of each element are retained. The properties of a ***compound*** of two elements are usually quite different from those of the original elements. The formation of a compound from elements is called ***synthesis,*** and the opposite process is ***decomposition.*** The chemical properties of a substance include its tendency to react chemically with other substances and the nature of energy changes in the reactions.

Hydrogen was discovered by Cavendish in 1750, and oxygen by Priestley and Schule in 1774. Lavoisier (1743–1794) showed combustion to be combination with oxygen, and demonstrated that ***in every chemical process the total mass remains constant.***

All matter is composed of 93 or 94 elements, of which some 88 are distributed in the ***lithosphere*** or earth's crust, the ***hydrosphere*** or liquid layer on the earth, and the ***atmosphere*** or gaseous layer.

Dalton advanced the two laws: ***all elements combine chemically in definite proportions of mass,*** and ***the ratios of the masses of the same two elements in various compounds are to one another as small integers.*** He concluded that each element is composed of a characteristic type of ***atom*** or indivisible unit. The ***molecule*** is the name given to the smallest stable entity of any element or compound. In 1811 Avogadro showed that ***equal volumes of any gases (under the same conditions) contain the same number of molecules.*** This observation, with Dalton's laws, made it possible to determine the relative ***atomic weights*** of nearly all the elements.

Mendeléeff and Meyer found recurring sequences of properties of the elements when arranged by atomic weight, that is, as a ***periodic table.*** The order number of an element in this table is called its ***atomic number. Atomic weights*** of the elements are fixed by choosing that of oxygen to be exactly 16.

The atomic theory has interpreted crystal structure and gaseous, electrical, and spectroscopic phenomena. Individual alpha particles (high-speed helium atoms) can be detected on a zinc sulfide screen, by electrical pulses in a ***Geiger counter,*** or by visible cloud tracks in a ***Wilson chamber.***

QUESTIONS

1. Why do we distinguish between ***physical*** and ***chemical*** phenomena? Is this distinction real or somewhat arbitrary?
2. What is a ***physical mixture?*** What methods are available for the separation of such mixtures?

3. With what properties of matter is the chemist chiefly concerned?
4. How do we know whether a given specimen of material is a *mixture,* a *compound,* or an *element?*
5. How small can we subdivide a piece of matter and still have it maintain its characteristics?
6. Should we call the early suggestions of Democritus and Leucippus, that matter is composed of elementary particles, more than pure speculation?
7. Is the definition of an element given by Boyle in the *Sceptical Chymist* satisfactory now?
8. Are ordinary physical processes violations of the principle of conservation of matter—that matter can neither be created nor destroyed? What about ordinary chemical transformations?
9. How do we make chemical combinations of atoms? Do atoms differ in the way they form combinations with other kinds of atoms?
10. Aluminum is believed to constitute a greater fraction (by weight) of the earth's crust than does iron. Why, then, is aluminum more expensive per ton than iron?
11. Does the concept of atoms seem essential in describing chemical processes involving the changes in composition and energy that occur when elements interact with each other?
12. Nitrogen and hydrogen are diatomic gases, that is, each molecule consists of two atoms. If one volume of nitrogen unites with three volumes of hydrogen to form two volumes of ammonia gas, what, then, is the simplest chemical formula that ammonia can have?
13. Are some of the 93 or 94 major kinds of elements still unknown?
14. Why was the general acceptance of the atomic nature of matter delayed until after the discovery of radioactivity by Becquerel in 1896, even though the earlier experimental work of Dalton, Gay-Lussac, and Avogadro on gases had clearly indicated the existence of atoms?
15. Are single atoms (about 10^{-8} cm in diameter) visible under a microscope? Can we prove by other methods that atoms really exist?
16. What do we mean by an *atom?* Is the word etymologically correct now?
17. Why must all the properties of matter, physical, chemical, biological, etc., depend ultimately on the characteristics of atoms and molecules?

Section III

ENERGY

CHAPTER VI

IDEAS ABOUT ENERGY

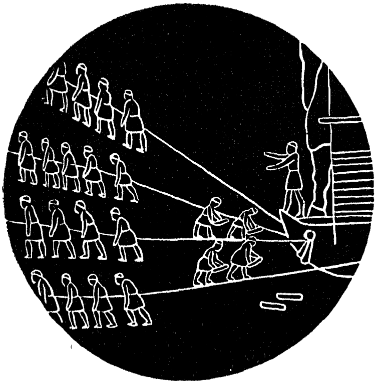
Energy and Civilization. Matter and energy are our natural resources. The degree to which these resources have been developed and used is one measure of man's civilization. In the beginning each man had only his own energy to use in the struggle for existence, although, if aggressive and strong enough, he soon subjugated fellow men and animals to do his work. Enslavement reached such a stage that Greek Civilization, at its peak, included about 5 million free men and 12 million slaves. The ideals of that time about democracy and the perfect social order could have had little force in practice under such circumstances.

RELATIVE ENERGY OUTPUT PER PERSON*

China	1
British India	1.3
Russia	2.5
Italy	2.8
Japan	3.5
Poland	6
Holland	7
France	8.3
Australia	8.5
Czechoslovakia	9.5
Germany	12
Belgium	16
Great Britain	18
Canada	20
United States	32

*After T. T. Read, "World's Output of Work," *American Economic Review*, v. 23, p. 55 (March, 1933).

Today controlled energy is our slave. Indeed, Van Loon has said, "The amount of mechanical development will be in inverse ratio to the number of slaves that happen to be at a country's disposal." In spite of much vague talk about men versus machines, no other factor has been so important in releasing peoples from



(*Yale and Towne.*)

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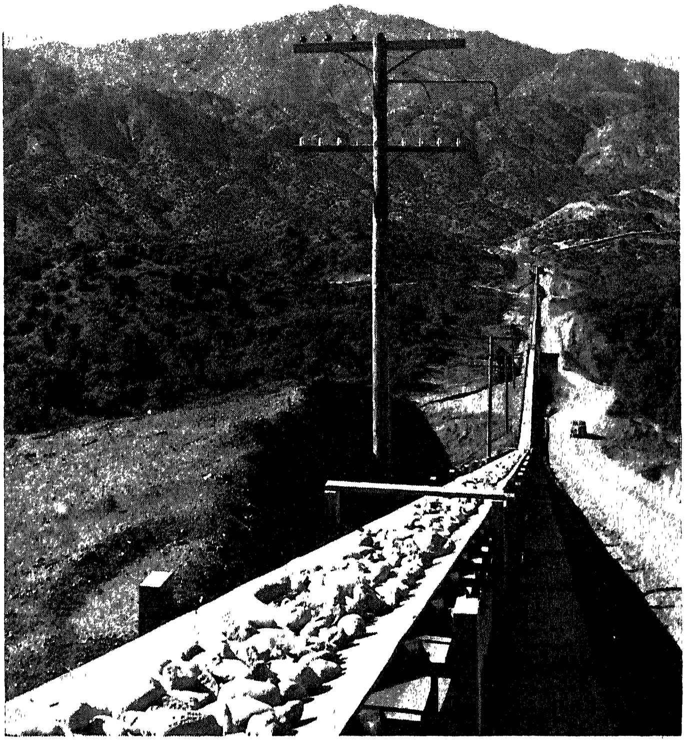


(*Engineering News Record.*)

b

Fig. 134. (a) Slaves provided the power for most primitive handling; (b) power, our modern slave. Ten-mile conveyer belt to haul 10 million tons of concrete materials for Shasta Dam.

human bondage as the great sources of energy in nature which intelligent use of machines has put to work for mankind.

The energy output per person probably shows as much about the standard of living of a country as any other factor. Professor Read in 1933 gave the estimates in the table on page 203.

The use of energy has made it possible for every person in the United States to have the equivalent of 30 slaves! No wonder the standards of living here are so high by comparison with other countries.

Energy, a Purchasable Commodity. Certainly energy is a purchasable commodity. When we buy coal to heat our houses and to run our power plants, we are buying heat energy. When we purchase food at the grocery store, or pay the check for dinner at a restaurant, we are primarily purchasing energy to keep our own body power plants running and to maintain our body temperature at the proper level. Even the clothes we wear have at least one practical purpose—to reduce loss of heat energy to the surroundings. The costs of many basic fuels per unit of available energy agree surprisingly well. Crude oil, soft coal, timothy hay, and pine pulp, for example, are all within the range of 0.10 to 0.15 cents per 1,000 kilocalories,[1] according to typical wholesale market quotations in this country.

Our social and economic system depends on the sale or exchange of matter and energy or the products of energy. This is quite obvious in the case of the day laborer who is paid for the amount of physical work he performs. A man who, as the result of training and native ability, can direct his efforts to present law cases at court, to perform delicate surgical operations, or to produce works of art is also compensated for his expenditure of energy, though the process is more complicated.

The machine age brought the energy concept and made it a practical basis for establishing values of necessities. Today's keen competition tends to force prices toward the level set by the cost of the energy involved in the collection, transportation, and processing of materials, in advertising, in maintaining governmental protection, etc. This is the foundation for various proposals that energy units should be used as the basis for our exchange system rather than gold and silver, which are otherwise com-

[1] The kilocalorie is the large calorie, an energy unit that is used principally to measure heat energy (see p. 232).

paratively useless. Such a change, however, might in itself be of little practical importance, because our currency values already tend to correlate themselves with energy units.

Since energy is so important in life and since its utilization is the foundation of technical progress, we ought to acquire a thorough understanding of its nature.

Early Ideas of Energy. It is easy to understand why the concepts of mechanical energy and work developed before ideas of other forms of energy. Men have always had to do physical work to provide for their existence. The meaning of mechanical energy, however, was not rigorously defined until the time of Newton, and the universal importance of energy in all natural phenomena was not appreciated until about the middle of the last century.

There are many ways in which work may be done, that is, in which energy may be transferred, but the concept of work probably develops most naturally in connection with the lifting of a weight through a definite distance. If we lift an object of a certain weight from one level to another, then lift it twice as high, we feel intuitively that twice as much work is done in the second case. Similarly, we would say that doubling the weight would double the work which is done in raising the object through a fixed distance. According to this, the work should depend on both the force producing the motion and the distance through which it acts. Remembering that intuition can serve as no more than a useful guide to scientific reasoning—it certainly cannot take the place of experimental evidence—let us examine the precise ideas about work to which these cruder views have led.

Mechanical Energy. The physicist has found these simple ideas about work quite satisfactory, with one reservation. Force must be considered a *vector* quantity; that is, it is not completely defined until both its magnitude and its direction are given.

The work done in moving an object is equal to the product of the applied force and the distance moved in the direction of the force.

If we simply lift an object vertically, the motion and the force that we apply are clearly in the same direction. Thus, if we lift a body weighing one newton through a distance of one meter, then the work done is one newton-meter. This unit is also called the

joule.[1] If we lift an object weighing one pound, through a height of one foot, the work done is one *foot-pound.* In such cases

$$\text{Work done} = wh = mgh, \text{ in foot-pounds (ft-lb) or joules (newton-meters)}$$

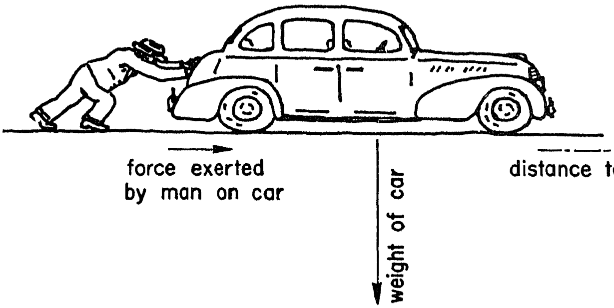


Fig. 135. The useful work done is the product of the force exerted on the car in the forward direction and the distance which the car moves.

where w is the weight, m the mass, g the acceleration due to gravity (page 149) and h the height. The relation between the two systems of units is such that

$$1 \text{ joule (or 1 newton-meter)} = 0.738 \text{ ft-lb}$$

or

$$1 \text{ ft-lb} = 1.356 \text{ joules (or newton-meters)}$$

We must be careful when the forces are not in the direction of motion. A modern light car has a mass of perhaps 1,500 kg, or weighs approximately 15,000 newtons. Suppose that it runs out of gas, and we have to push it 100 meters on a level road to a filling station. Is the work that we do equal to 15,000 newtons × 100 meters or 1,500,000 joules? Fortunately not! The weight is not in the direction of motion, in fact, it is at right angles to it, and therefore has no part in the consideration. The force F, which must be exerted ***in the direction of motion*** to move the car horizontally, actually has to overcome only frictional forces, largely internal friction in the wheel bearings of the car if the road is smooth. This force might be about 1,000 newtons, so the work done would be only 1,000 newtons × 100 meters, or 100,000 joules.

For those who remember their trigonometry, these ideas may be expressed very simply in a more general way. The work done by

[1] If another metric unit of force, the ***dyne*** (10^{-5} newton), is used, the unit of work is the ***dyne-centimeter,*** which is called the ***erg.*** One ***joule*** is 10^7 ergs.

a force F in moving an object a distance d, is

$$\text{Work} = Fd \cos \theta$$

where θ is the angle between the force and the direction of motion. If the angle is 90 deg, as between the weight of the car and the direction of motion of the car, cos 90 deg = 0, so no work is done. If $\theta = 0$ deg, $\cos \theta = 1$, so the work is Fd, as is the case if F represents the frictional force.

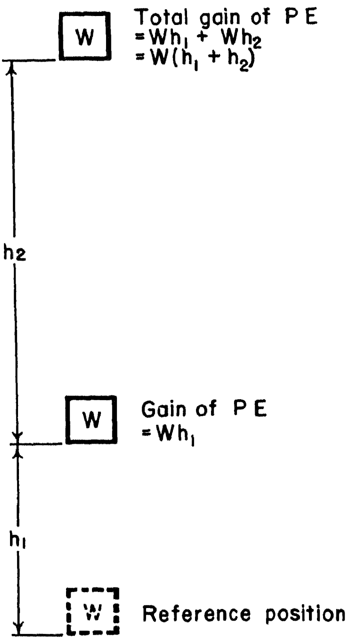


Fig. 136. An object gains potential energy when it is lifted. The amount equals the weight times the increase in height.

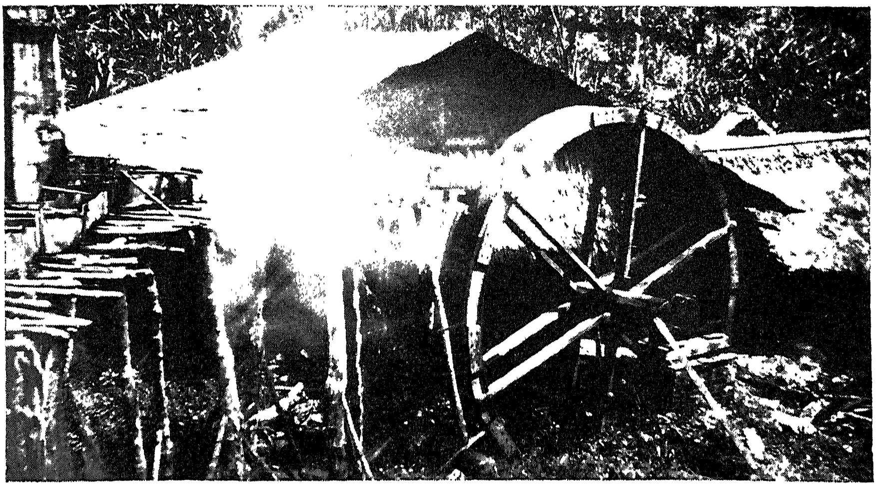
Potential Energy or Stored Energy. All of us are familiar with at least two forms of stored mechanical energy: ***gravitational potential energy*** and ***elastic potential energy.***

Gravitational Potential Energy. If we lift a 1-lb weight 3 ft vertically from the floor, we say that we have done *3 ft-lb* of work on the weight. Physicists say that this weight has gained 3 ft-lb of ***potential energy*** because of its elevated position above the floor, that is, ***it*** can do 3 ft-lb of work if it is allowed to fall to the floor. Thus the potential energy gained by a body is

$$\text{PE} = wh = mgh$$

in foot-pounds or joules (newton-meters), where w is its weight, or m its mass, and h is the distance it is raised.

We must be cautious, however, in referring to ***total*** gravitational potential energy, which obviously depends on the elevation from which we take the measurement. The 1-lb weight raised 3 ft has 3 ft-lb of potential energy ***with respect to the floor,*** or, as we said before, it has simply ***gained*** 3 ft-lb of potential energy. If we are on the twelfth floor of a building, the floor is about 140 ft above the ground. When lifted above the floor 3 ft, the weight has 3 ft-lb of potential energy with respect to the floor, but $(140 + 3)$ ft $\times$ 1 lb or 143 ft-lb potential energy with respect to



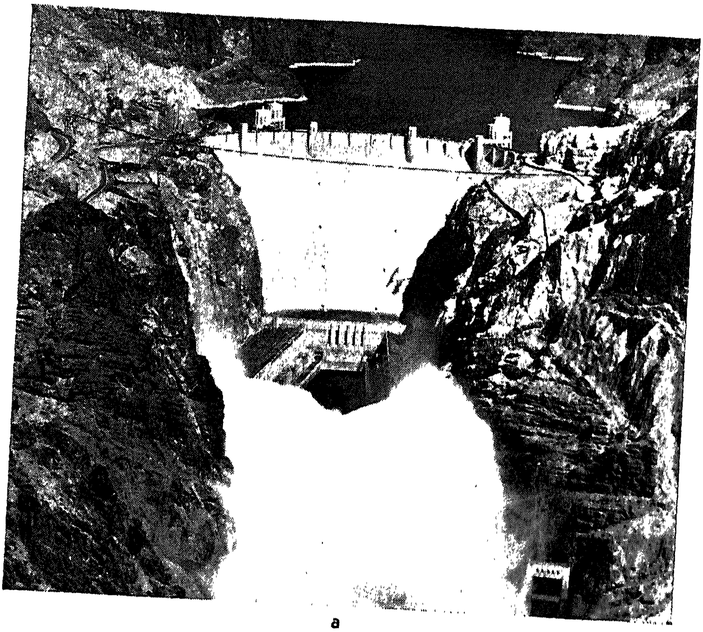
(*General Electric Company.*)

Fig. 137. Primitive water wheel to furnish power for grinding sugar cane.

the ground. Actually, the weight would not cease to have potential energy until placed at the center of the earth, and then only if gravitational forces of the moon, sun, and other bodies in our solar system were disregarded. Potential energy of position is then only ***relative,*** and we must be careful to consider from where it is to be measured in each particular case. For most purposes the earth's surface makes a convenient reference surface from which to calculate gravitational potential energy.

Elastic Potential Energy. When elastic bodies are deformed, we have seen that internal forces proportional to the distortion tend to restore the original forms (Hooke's law). These forces can do work when released; hence elastically distorted bodies have stored energy, or potential energy. The work done in deforming the body is at least equal to the work that the distorted body can do when released, because we cannot get something for nothing. One of the most common applications of stored energy is in spring-driven clocks and watches.

Sources of Potential Energy. Long before the Christian era, men had devised crude water wheels to make some use of one great source of potential energy which exists in nature. The sun daily "lifts" huge quantities of water from the oceans by evaporation; later this water is deposited as rain on land high above sea level. Herein there is an enormous supply of potential energy. The water



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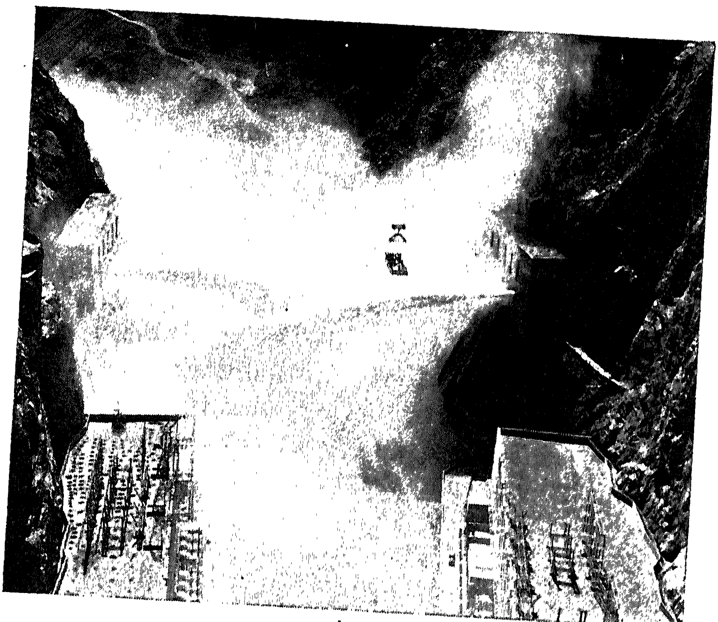

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(*General Electric Company.*)

Fig. 138. Boulder Dam. (a) Water through outlet valves appears in foreground; (b) water streams from outlet valves, indicating the tremendous kinetic energy available. Power generating plants are in the foreground.

rushes down the mountain sides and finally returns to the sea. Where the land contours are suitable and water flow adequate, the construction of dams permits storage of large amounts of this water at a considerable height above the surroundings, so that its potential energy can be utilized to do work. It is a far cry from primitive water wheels to the great hydropower projects of today, but the principles are essentially the same. Modern water turbines are really refined water wheels. In this country at Boulder Dam, at Niagara Falls, in the Tennessee Valley, in the Columbia River Valley, and at the Mississippi River development at Keokuk, Iowa, typical public and private projects seek to utilize the potential energy of water.

The great Boulder Dam is 786 ft high and eventually will hold some 10^{13}, or 10 trillion, gallons of water in the lake formed in the canyons behind it. Some of these projects, of course, have supplementary purposes such as flood control, the extension of navigation routes, irrigation, and reclamation. All have the great advantage that they utilize a tremendous natural source of energy which is continually replenished, whereas the consumption of our limited supplies of coal, gas, and petroleum drains away the irreplaceable potential energy stored in past ages. From the standpoint of conservation of natural resources, this is most important. At present we generate only about 40 per cent of our electric energy from water power. Conservative estimates show that we can develop at least five times as much energy from this source. At this time, however, there is perhaps not sufficient economic justification for such an expansion, and, as we shall see later, the other sources of energy have certain advantages which prevent their displacement.

We know many other types of stored energy. Every molecule is a result of forces between atoms. Available chemical energy is stored in coal, gasoline, kerosene, gas, and other typical hydrocarbon compounds. Electric energy and heat energy may be stored in several ways. Physics and engineering are much concerned with the various forms of energy and with the transformations of energy from one form to another.

Kinetic Energy. A car dashes along the road at 80 miles per hour. Suddenly the driver loses control, and the car crashes head-on into a reinforced concrete bridge structure, demolishing many feet

of bridge railing and crushing the whole front end of the car before it is brought to rest! This is a tragic illustration of the fact that all objects in motion possess energy—***kinetic energy***—and that this energy must be used up in doing work before the objects come to rest. Unfortunately, in this case the work done was not useful.

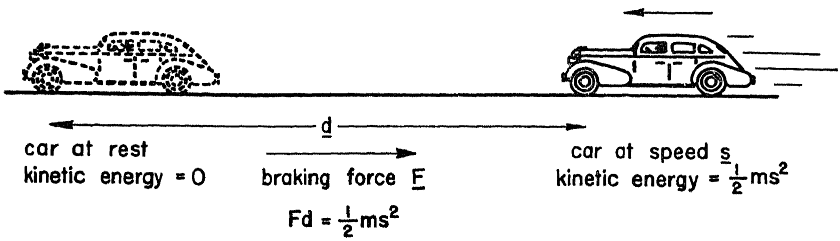


Fig. 139. The loss of kinetic energy equals the work done against friction in stopping the car.

The energy of motion, or kinetic energy (KE), of a moving object may be expressed

$$\text{KE} = \frac{1}{2}ms^2 = \frac{1}{2}\frac{w}{g}s^2, \text{ in joules (newton-meters) or ft-lb}$$

where m is the mass, s is the speed, w the weight, and g the acceleration due to gravity, all measured in the appropriate units. In the metric system, if m is in kilograms, g in meters per second per second, and s in meters per second, then the kinetic energy is in ***joules*** (newton-meters), the same units as those for potential energy. In the English system, if w is in pounds, g in feet per second per second, and s in feet per second, then kinetic energy is in ***foot-pounds,*** as we might expect.

Just what happens when we stop a moving object such as a car? A moving car has kinetic energy and will keep moving until all its kinetic energy is transferred to energy of another form. Normally we stop a car by using brakes, which are simply devices for obtaining a retarding force. The car then will go forward until the work done, that is, the total retarding force F applied to the car times the distance d it goes, is equal to the kinetic energy that the car had before the brakes were applied. Then, if we consider that F is reasonably constant while the car is stopping

$$Fd = \tfrac{1}{2}ms^2$$

Suppose that a car weighing 3,200 lb is traveling at the rate of 30 miles per hour (44 ft/sec). If it has modern hydraulic brakes

in good condition and good tires which have large frictional forces against dry pavement, then the braking force (the total force of wind, and of pavement against tires) may be as much as 3,500 lb. Then (remembering that $m = w/g$)

$$(3{,}500 \text{ lb}) \times (d \text{ ft}) = \frac{1}{2}\left(\frac{3{,}200 \text{ lb}}{32 \text{ ft/sec}^2}\right) \times (44 \text{ ft/sec})^2$$

Solving for d, we find the distance about 28 ft.

Since the kinetic energy increases as the square of the speed, if the car is going 60 miles per hour it will require a stopping distance of 110 ft, and if 90 miles an hour—250 ft!

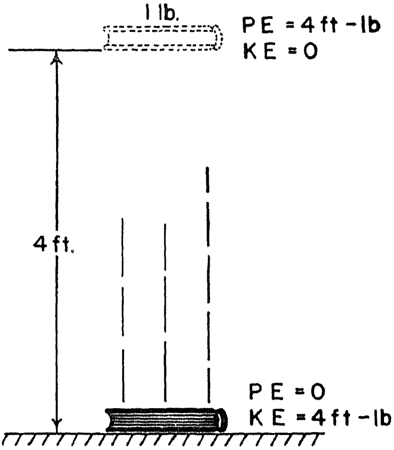


Fig. 140. When an object falls, potential energy changes to kinetic energy.

No wonder so many accidents occur at high speeds. Few people realize how much the distance required to stop a car increases with speed, even under the best conditions. Furthermore, studies have shown that the average reaction time required to ***decide*** to stop and then to begin to apply the brakes is usually not less than one-half second. At 90 miles per hour, the car may go 66 ft even before the brakes are applied.

Conversion of Mechanical Energy. Suppose that we raise a 1-lb book 4 ft from the floor. We say we have done $F \times d = 4$ ft-lb of work on it, and that it has gained, therefore, 4 ft-lb of potential energy. If we then let the book fall freely, its speed continues to increase, because of the acceleration due to gravitational force, until it hits the floor. What has happened to its potential energy? Careful experiments have shown that just at the moment before it hits the floor all of the ***potential energy*** given to the book has been ***converted*** into ***kinetic energy*** (except for the small effect of air friction). Experiments on freely falling bodies, of the type initiated by Galileo, show that the speed is given by

$$s = \sqrt{2gd}$$

where d is the distance fallen. For the falling book, $d = 4$ ft, $g = 32$ ft/sec^2; so $s = 16$ ft/sec. Its ***kinetic energy*** is defined so that

$$\text{KE} = \frac{1}{2}\frac{w}{g}s^2 = \frac{1}{2} \times \frac{1\text{ lb}}{32\text{ ft/sec}^2} \times (16\text{ ft/sec})^2$$
$$= 4\text{ ft-lb}$$

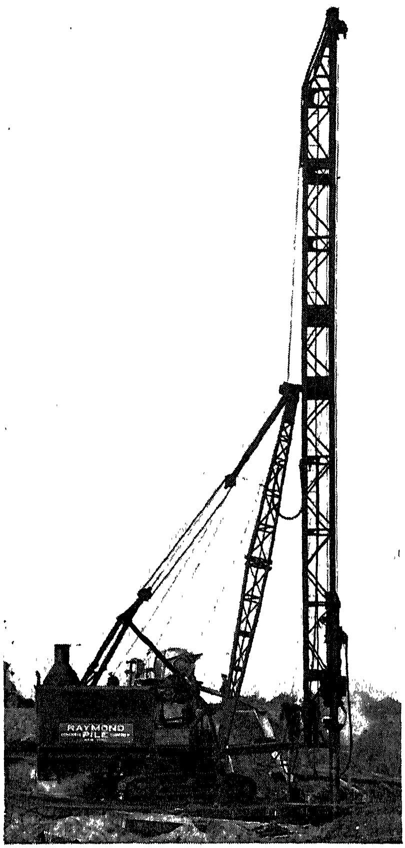
Hence the kinetic energy, 4 ft-lb, is just the decrease in potential energy. There is nothing mysterious about this, because, if we square both sides of $s = \sqrt{2gd}$ and multiply them by $\frac{1}{2}m$, we get

$$\tfrac{1}{2}ms^2 = mgd$$

But $\frac{1}{2}ms^2$ is what we call kinetic energy, and mgd is change of gravitational potential energy, so the expression $s = \sqrt{2gd}$ really says:

$$KE = PE$$

Thus, we have ***defined*** kinetic energy and potential energy so that the kinetic energy gained by the book and the potential energy lost by it must turn out ***experimentally*** to be equal.



(*Raymond Concrete Pile Company.*)

Fig. 141. Pile driving rig.

Such conversions of potential into kinetic energy and the reverse are very common. They are widely used in devices for driving piling for supports of bridges, elevated highways, etc. In the older form of pile driver, a heavy weight, perhaps 500 lb, is slowly raised to a height of, say, 20 ft, thereby gaining 10,000 ft-lb of potential energy, and then is released. Its kinetic energy as it hits the piling is then also 10,000 ft-lb. All of this kinetic energy has to be accounted for as work done on the piling. We know then that the average force exerted on the piling times the distance moved must be equal to the kinetic energy. If the piling moves, say $\frac{1}{4}$ ft, we have

$$F \times \tfrac{1}{4}\text{ ft} = 10{,}000\text{ ft-lb}, \qquad \text{or} \qquad F = 40{,}000\text{ lb}$$

a tremendous force! Modern types of such giant hammers use steam or compressed air to exert additional downward forces.

Another example of exchange between potential energy and kinetic energy appears in the simple pendulum. If we pull the

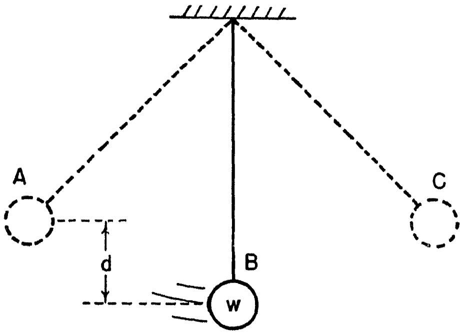


Fig. 142. Pendulum. The kinetic energy at B becomes potential energy at A or C.

weight w up to position A (Fig. 142), a height d above its lowest position, we give it a potential energy of wd. If we release the weight, it gains speed until at position B the potential energy becomes zero, its speed is greatest, and it has kinetic energy only. Then it loses kinetic energy and gains potential energy until at C it again has only potential energy. So it goes back and forth, its energy appearing first in one form, then in the other. Between A and B, or B and C, the total energy is the same, but it is divided into the two forms, so that we may say at all times

$$\text{PE} + \text{KE} = \text{constant (neglecting friction)}$$

Why, then, does a pendulum, no matter how carefully mounted, always swing with gradually decreasing amplitudes? The answer is that at each swing some small fraction of its energy is "lost" in doing work against frictional forces exerted at the bearing and by the air. Actually we know that the energy "lost" is not really lost, but merely converted into another form, ***heat energy.***

THE CONSERVATION OF ENERGY

From experiments on mechanical energy conversions, physicists were gradually led to what is perhaps the most general conclusion of all science. Energy may be transformed into many different forms, but the original amount of energy can always be accounted for after the change, that is, the books always balance. We shall

learn later that matter must also be considered a form of energy, and with this in mind we can say: ***Energy can neither be created nor destroyed, it can only be transformed.*** This principle, which covers all natural phenomena so far discovered, is exceedingly useful.

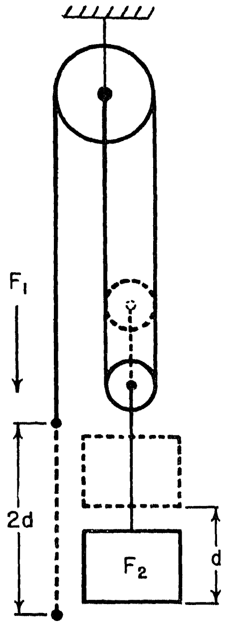


Fig. 143. Pulley system. To raise the weight a distance d, the end of the rope must be moved a distance 2d.

In a more general sense, then, doing work on a body simply means transferring energy to that body from the man or machine that does the work. We have seen that for most simple mechanical systems we need usually consider only three forms of energy: potential energy, kinetic energy, and energy transferred into heat energy because of friction. The principle of conservation of energy then summarizes what we have already learned, in the statement that, for mechanical systems, we have

$$\begin{aligned}\text{Work done on a body} = {} & \text{PE added to body} \\ & + \text{KE added to body} \\ & + \text{energy converted into heat by friction}\end{aligned}$$

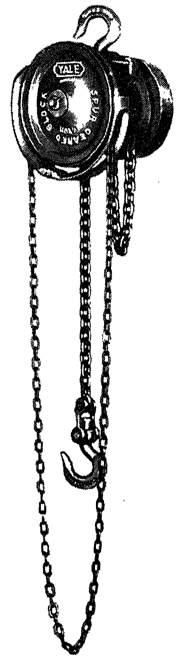
Machines. Machines are simply devices to adapt forces to special purposes. We use countless machines today—levers, pulleys, wheels and axles, etc. But all of them are useful chiefly because they enable men, animals, or primary sources of energy such as electric motors or gasoline engines to exert forces in proper directions or of desired magnitudes, so as to meet specific needs.

Mechanical Advantage. Why do we use machines? Let us consider a simple machine, say a pulley system, to illustrate characteristics of all machines. The force F_1 applied to the machine causes the machine to exert a force F_2. We say that

$$\frac{F_2}{F_1} = \textit{mechanical advantage}$$

In the case illustrated in Fig. 143, a little thought shows that if there were no friction, and if the weight of the pulleys and ropes were neglected, the pulley system here would exert a force F_2

which is twice the force F_1 applied to it. This is apparent because the two sides of a doubled rope support the lower pulley and the weight, the tension everywhere in the rope is the same, and the actuating force is applied to an end of this same rope. The mechanical advantage of this system is then two. However, no energy is gained because the applied force must be moved through *twice* the distance that the useful load moves. By changing the geometrical design of a machine, for example, by using more pulleys, it is possible to increase the ratio of the forces to much larger values. In automobile lift jacks, it is essential to be able to lift 1,000 lb or more by applying a force of even less than 50 lb. Thus with machines we can exert much greater force than would be possible directly.



(Yale and Towne.)

Fig. 144. Chain hoist for handling 1½ tons.

Speed Advantage. In the case of the pulley we gained mechanical advantage but lost in speed in the same ratio. For many machines, such as hand-turned grind wheels, it is desirable to increase the speed, that is, have large ***speed advantage***. This must be done by having mechanical advantages less than 1, so the actuating force on the machine must be greater than the force which the machine exerts on the load.

Efficiency of Machines. From the law of conservation of energy we know that the useful work F_2d_2 done by a machine is less than the work performed on the machine by the amount of energy converted into heat by friction, or

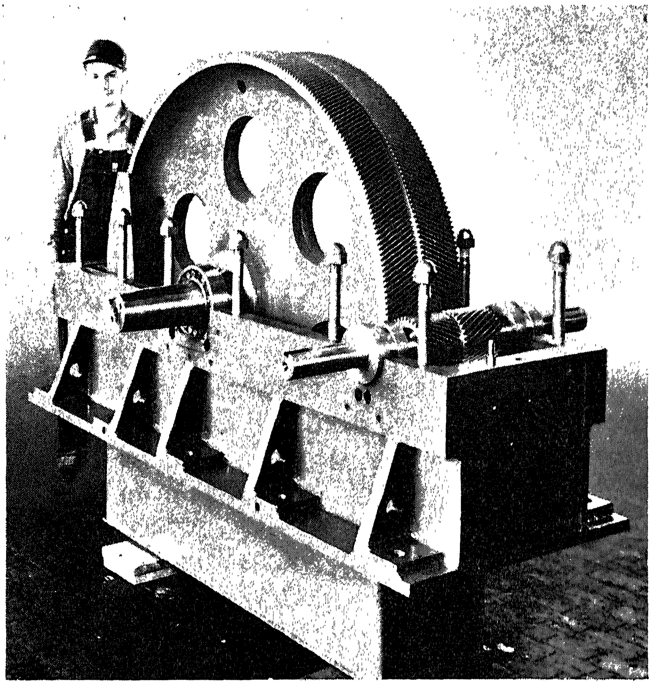
$$F_1d_1 = F_2d_2 + \text{energy converted into heat by friction}$$

The efficiency of a machine

$$\frac{\text{Energy output}}{\text{Energy input}} = \frac{F_2d_2}{F_1d_1}$$

therefore, can never be greater than 1 (or 100 per cent). As the efficiency of actual machines is always less than one (less than 100 per cent), ***all*** machines thus far built have some energy "loss" by conversion into heat energy through friction.

We always lose energy when machines are used, and never gain energy. Why do we use machines then? Primarily because we can exert greater forces, increase speeds, or direct forces advantageously, so, while energy is actually lost, machines make it possible to accomplish tasks otherwise beyond our powers.

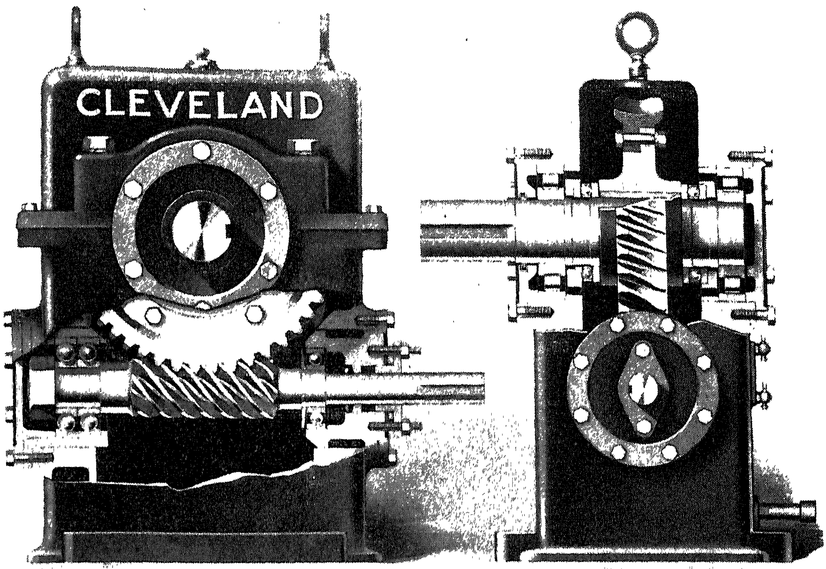


(*SKF Industries.*)

Fig. 145. Driving gears for a large mill.

Friction Has Many Valuable Uses. Because it reduces the efficiency of machines, one might believe that friction is always bad. Far from it, for this would be a queer world without friction. If there were no friction, our houses would fall apart because nails would no longer hold. We could not walk because our feet would always slip. Our motor cars could not move uphill, and still worse, once moving they could not be stopped, for the brakes would not hold. In fact, it would be practically impossible to control the motion of any machine.

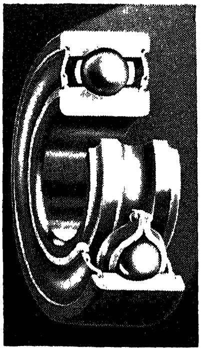
Machines and Society. From an economic standpoint, and from the standpoint of conservation of natural energy resources, it is obviously important to increase the efficiency of machines. The energy converted into heat is ordinarily useless and can never be



(*Cleveland Gear Works.*)

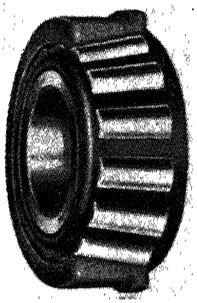
Fig. 146. Speed reducer using worm and toothed wheel. Machine serves to change both speed and direction of rotating shaft. Efficiency usually above 95 per cent.

fully recovered, although it is sometimes possible to use for other purposes a part of the heat developed. There is continual research to improve the efficiency of machines. Frictional losses in bearings, for example, have been reduced greatly through the use of improved ball or roller bearings and through proper lubrication. The actuating force necessary in a given machine can often be reduced by redesigning the whole machine, using fewer and lighter parts of less dense alloys. In new railway cars, which are lighter yet fully as strong as those of older design, the use of special roller bearings has in some cases reduced by one-half the force required to pull an empty car, the "dead load." An automatic machine which in a moment stamps out an automobile body almost complete in a single operation, where formerly many men worked by hand for a long time on a multitude of small pieces, reduces by a big factor the costly human energy needed. Often the development of entirely new processes to accomplish a given purpose, perhaps a new method of refining ore, results in a tremendous saving in the energy involved and, therefore, in the cost of production.



(*SKF Industries.*)

a



(*Timken Roller Bearing Company.*)

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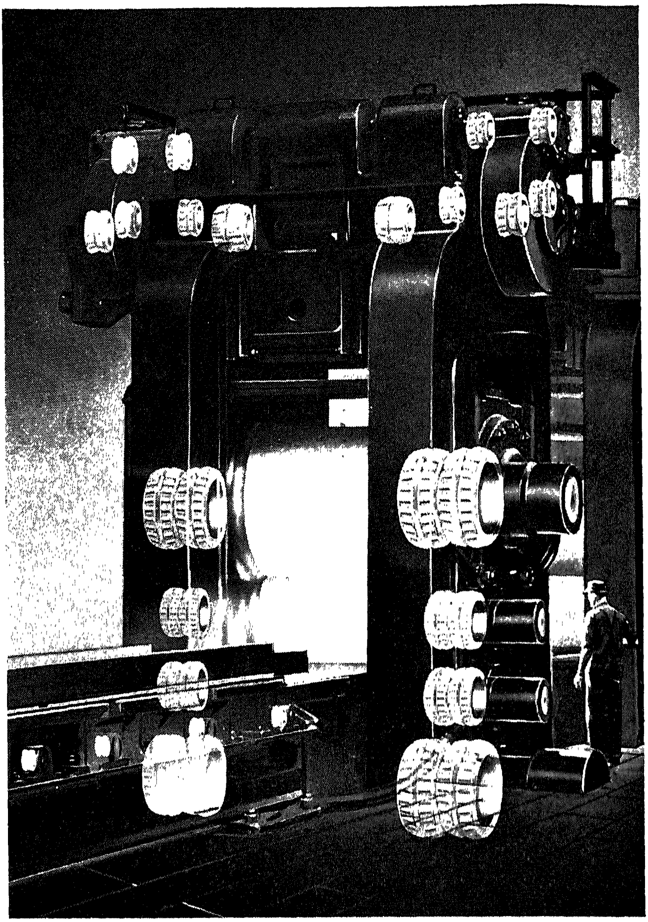

(*Timken Roller Bearing Company.*)

c

Fig. 147. Bearings designed to minimize friction on rotating shafts. (a) Sealed ball bearing; (b) roller bearing; (c) location of bearings in a large rolling mill.

Improved efficiency of industrial processes is unquestionably of great importance to all. Whether or not increased efficiency in a given machine is of immediate general benefit depends on many factors in the social order. In the long run, increases in efficiency and increased use of energy are definitely desirable, but it must be recognized that rapid social readjustments present serious problems. Because our social order is a democracy, the responsibility for decisions concerning these readjustments rests with each individual. This calls to attention the need for understanding the

applications of science, and consequently the fundamentals of science. In other words, it may be an almost fatal mistake if we think of the "social sciences" as being independent of science.

Power. The time required to do a given amount of work is often an important factor. ***The rate of doing work is called power*** and it is essential to distinguish it carefully from work or ***energy,*** for these terms are badly confused in the popular mind.

$$\text{Power} = \frac{\text{energy}}{\text{time}}, \text{ in } \textit{watts} \text{ (newton-meters/sec or joules/sec),}$$
$$\text{or in ft-lb/sec.}$$

In the metric system, 1 newton-meter/sec or 1 joule/sec equals 1 watt, the commonly used unit of electric power. Thus, comparisons between electric and mechanical power and energy measurements are very easy. Before the machine age developed, the rate at which an average sort of horse could do work came to be used as a basis for power measurements. Of course, it would be difficult to keep a standard horse at a Bureau of Standards for purpose of comparison, so for convenience it was eventually agreed that

$$1 \text{ horsepower} = 550 \text{ ft-lb/sec}$$

In terms of watts, the equivalence is

$$1 \text{ horsepower} = 746 \text{ watts (or joules/sec)}$$

The Human Machine. The human machine is surely the most interesting of all machines. Even the lowest forms of living matter are exceedingly intricate mechanisms, so intricate in fact that scientists are only beginning to untangle the multitude of physical and chemical processes that take place in them.

It is possible to measure the rates at which the human machine does work in various activities. Physiologists, particularly, consider such measurements important in the study of body metabolism, the transformation of food into various energy forms in body processes. Studies of this type have confirmed the law of conservation of energy with respect to biological processes of all kinds. Following are some typical results of measurements of human power output.

HUMAN POWER OUTPUT

Type of work	Time of maintenance	Power output (approximate)	
		Hp	Watts
Walking on level	10 hr to several days	0.05	40
Mountain climbing:			
Moderate	Many hours	0.1	80
Strenuous	1–2 hr	0.2	150
Very strenuous	1 min	3	2,000
Running—maximum speed	5–10 sec	10	7,000

How much work does a man do when holding a heavy weight? Physicists have had to define mechanical work as the force times the distance moved, and in this sense the work done is zero. Physiologists do not yet agree upon the way in which muscles exert a force without any accompanying motion, but it seems probable that a great many individual muscle cells are continually twitching, and the steady force exerted is the average effect of these small superimposed motions. Thus chemical energy is used internally when we try to substitute our flexible muscles for the bracing of a rigid support. This energy, however, is turned directly into heat instead of contributing to external useful work, unless motion is involved.

Perpetual Motion. The fantasy of so-called perpetual motion machines has intrigued men for many centuries, and otherwise intelligent men have spent much time and effort in designing ingenious and intricate machines to accomplish what we know today to be fundamentally impossible. Such machines are intended to continue to run indefinitely and do unlimited work without decreasing their own energy or losing their ability to continue to do work. Naturally a machine of this sort would be very useful. No one has ever succeeded in building such a device, and no one ever will, for its basic hypothesis is clearly contradictory to all known facts about the behavior of matter and energy as expressed in the principle of conservation of energy.

The total energy input to a machine must always be at least as great as the useful energy output in order to maintain a process. This is equivalent to the statement that the efficiency can never

be greater than one. So far, it has proved impossible to eliminate completely energy "losses," usually of frictional type; hence all machines have been less than 100 per cent efficient. Once started, man-made machines cannot even maintain their own operation indefinitely, let alone do additional work. This brings up numerous examples in nature of quite continuous motion over a long period, as, for example, the earth rotating on its axis. However, if the energy of the earth's rotation could be used to do work, its speed and thus its rotational energy would continually decrease. It has been estimated, for example, that tidal friction is sufficient to increase the time of rotation of the earth about 1/1,000 second per century.

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SUMMARY

Energy plays an important part in our economic life and is a purchasable commodity.

The ***work*** done in moving an object is the product of the applied force and the distance moved in the direction of the force. We shall use the ***joule*** or newton-meter, as the metric unit of work or energy, and the ***foot-pound*** as the English unit.

Energy that is "stored" is called ***potential energy*** (PE). The ***gravitational*** potential energy of an object is

$$\text{PE} = \text{weight of object} \times \text{height above reference position}$$

An elastically distorted body possesses ***elastic*** potential energy. Important sources of potential energy are water which is above sea level, and natural fuels.

Energy of motion is called ***kinetic energy*** (KE). The kinetic energy of a moving object is

$$\text{KE} = \tfrac{1}{2} \times \text{mass of object} \times (\text{speed of object})^2$$

Kinetic energy and potential energy have the same units as work, that is, the joule and the foot-pound.

Potential energy may be changed to kinetic energy and kinetic energy to potential energy, but some of the energy changes to heat energy. The law of conservation of energy, probably the most fundamental in science, is: ***energy can be neither created nor destroyed, it can only be transformed.*** In purely mechanical systems

$$\text{Work done on a body} = \text{PE added to body} + \text{KE added to body} + \text{energy converted to heat by friction}$$

Machines adapt forces to special purposes. For a machine

$$\text{Mechanical advantage} = \frac{\text{exerted force}}{\text{applied force}}$$

From the law of conservation of energy

$$\text{Work done on machine} = \text{useful work done by machine} + \text{energy converted to heat by friction}$$

Thus

$$\text{Efficiency} = \frac{\text{useful work done by machine}}{\text{work done on machine}}$$

must be less than one. Although some friction is essential for the control of machines, the reduction of friction to decrease waste of energy is an important problem.

Power is the rate of doing work, or

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

Our metric unit of power is the ***watt*** or joule per second. The English units are the ***foot-pound per second*** and the ***horsepower*** (550 ft-lb/sec).

The human body may be regarded as a machine the activity of which can be described in terms of efficiency, power output, etc.

The law of conservation of energy tells us that "perpetual motion" machines are fundamentally impossible.

QUESTIONS

1. What primarily do we buy when we purchase food, electricity, coal, gasoline, or gas?
2. Can you justify the use of energy as a basis of value?
3. Why did the concept of ***mechanical energy*** develop before ideas of other forms of energy?

4. How do we use the following expression to measure energy or work?

$$\text{Energy} = \text{force} \times \text{distance (newtons} \times \text{meters or lb} \times \text{ft).}$$

Must the force be in the same direction as the motion?
5. If a force of 150 lb is used to move a 3,200-lb car a distance of 20 ft, how much energy is involved?
6. Are the units *foot-pounds* or *newton-meters* (joules) adequate to measure all mechanical energy?
7. Why is the physicist so interested in "units" or "dimensions"?
8. With what examples of potential energy, or stored energy, do you come in contact in everyday life?
9. Is the following expression adequate?

$$\text{Potential energy} = w \times h \text{ (newton} \times \text{meter or lb} \times \text{ft)}$$

10. Since gravitational potential energy depends on the height, it is always "relative." What about other forms?
11. A certain oil company has advertised that a gallon of its gasoline will lift a 3,000-ton locomotive 15 ft. How much potential energy per gallon does this indicate? In what form is this energy?
12. How must we use the relation

$$\text{KE} = \tfrac{1}{2}ms^2$$

to measure the energy of moving bodies?
13. Does kinetic energy have the same units, joules or foot-pounds, as potential energy? How are the quantities that enter into the expression for kinetic energy defined, and what units do they have?
14. What happens when a book falls from the table? Are we justified in believing that all of the potential energy of a body relative to the ground is converted into kinetic energy if it falls to the ground?
15. Cars have occasionally skidded off the 125th Street viaduct in New York City during icy or wet weather, and plunged about 75 ft to the street below. How much potential energy would a 4,000-lb car have before the plunge just as it was poised on the edge of the viaduct? How much kinetic energy would it have as it hit the street? What would have happened to the kinetic energy?
16. How much of the mechanical work in industry is based on conversion of potential to kinetic energy? Where does the energy come from originally?
17. How can we measure energy, directly or indirectly, in actual practice?
18. At what rate is the human machine capable of doing work, say when making a standing jump? That is, can we get some idea of what its maximum ***power*** or ***rate of doing work*** is, in foot-pound per second, or watts (joules per second)?
19. What does the principle of conservation of energy really mean? Does the total amount of energy involved in physical and chemical processes remain constant?
20. How does the principle of conservation of energy apply to cases where mechanical energy is transferred from one form to another, or from one machine to another, as by a chain or belt drive, or through gears?
21. Does the expenditure of a certain amount of mechanical energy necessarily result in the appearance of exactly that same amount of mechanical energy elsewhere?
22. When we speak of a machine having an efficiency of 50 per cent do we imply that 50 per cent of the energy has gone out of existence?
23. Can we say in general that mechanical energy input = mechanical energy output + energy converted to other forms?

CHAPTER VII

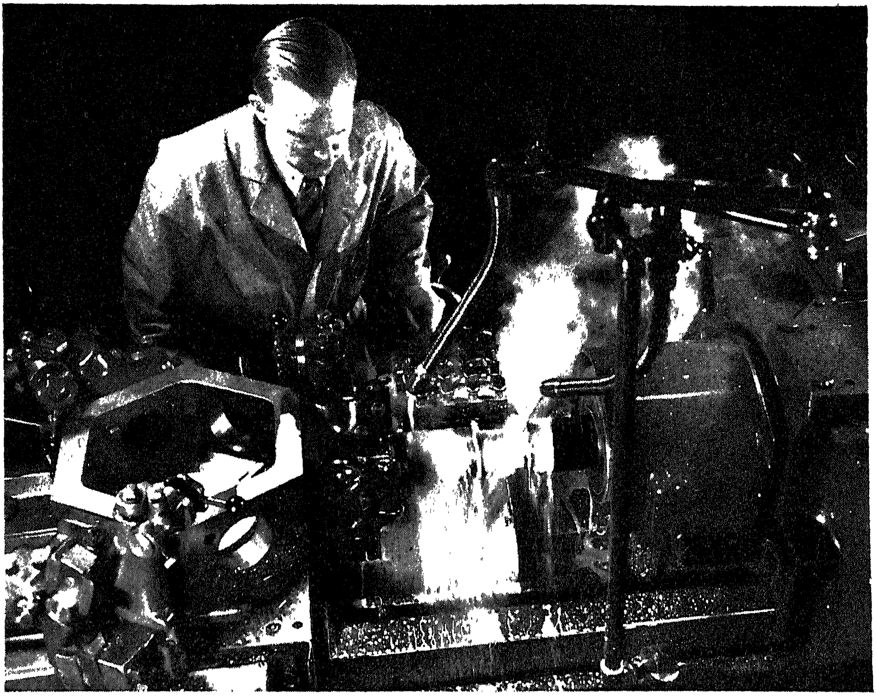
HEAT ENERGY

The concept of heat as an aspect of energy was long in developing. The alchemists and early chemists believed that combustion was connected with a mysterious stuff called "phlogiston" which was somehow released by all substances when they burned. Essentially the same idea was held by another group of early chemists and physicists who believed that water over a fire became hot because a subtle weightless fluid called "caloric" was added to it.

It remained for a New England Tory, Benjamin Thompson (1753–1814), to introduce a new conception of heat. Thompson, given the title Count Rumford in Germany, was a soldier of fortune and an experimenter extraordinary. In Europe, while supervising the boring of cannon, he was impressed by the enormous amount of heat produced when the heavy bit turned by horses slowly gouged out the metal to form a smooth bore. He made measurements of temperatures of water in the cavity, and showed conclusively that the temperature rise was simply proportional to the amount of mechanical work done on the cannon. Furthermore, the water could even be made to boil when a blunt bit was turned long enough. He concluded that heat must have been produced by the mechanical work done against the great frictional force acting on the bit, and that heat itself must be some sort of internal "motion." This was the start of a long series of experiments which identified Thompson's heat "motion" with molecular motion and led to our modern ideas of heat.

WHAT IS TEMPERATURE?

Before we discuss the measurement of ***heat energy*** we must be certain that we understand clearly the meaning of temperature. As will develop later in our studies of the kinetic theory of matter, the temperature in a region is nothing more than a quantity that depends on the average kinetic energy of molecules in that region.



(*American Machinist.*)

Fig. 148. Lathe work being cooled to take away the large amount of heat developed while a heavy cut is taken.

The molecules of any material are in rapid and continual motion, and all types of molecule at the same temperature have the same average kinetic energy. The value of this molecular kinetic energy is $\frac{1}{2}ms^2$, in which m is the mass of one molecule, and s^2 is the average of the square of its speed. When we add heat energy to a body in a fixed state, we simply increase the average speed of its molecules, and its temperature rises proportionally to the increase in average molecular kinetic energy. The temperature will become truly zero only when molecular motion becomes zero, and this temperature, which we call ***absolute zero,*** can be shown to be -273.16 degrees centigrade. Actually it would have been simpler for many purposes if we had used absolute zero as the zero of our temperature scale, rather than the freezing point of water as in the centigrade scale. To simplify the description of many physical and chemical phenomena, such as the expansion of gases, we shall introduce such a scale later, the ***absolute*** or ***Kelvin scale.***

Measuring Temperature. Man has the problem of measuring temperatures on earth which range from below the melting point of helium, $-272.2°C$,[1] to temperatures in arcs almost twice that in an oxyacetylene flame:

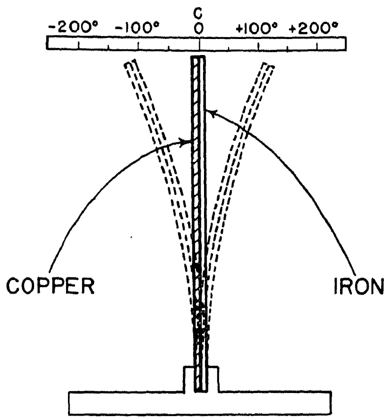


Fig. 149. Bimetallic strip.

Oxyacetylene flame.........	3500°C
Carbon arc (cored).........	5500°C
Iron arc...................	6020°C
Tungsten arc..............	6440°C

The sun's surface is at about the same temperature as a tungsten arc. Instantaneous temperatures, such as those obtained through exploding wires by means of high-voltage discharges, are estimated to extend to 20,000°C. This is actually near the maximum surface temperature of stars (approximately 30,000°C). Although the cooler outside layers hide from us the central portion of a star, theories of stellar structure indicate that the temperatures of star interiors may run as high as 20,000,000°C.

Ordinary Thermometers. Any phenomenon that varies with temperature can be used in principle to measure temperature. Most solids, liquids, and gases expand with increasing temperature, and this property is used commonly as an indicator of temperature difference.

Mercury and alcohol, when liquid, expand appreciably with moderate increase in temperature, and hence make good "thermometric" substances. All of us are familiar with the mercury-in-glass type of thermometer for common temperature ranges. Mercury solidifies at $-39°C$ and boils at 357°C, alcohol at $-117°C$ and 78.5°C. These properties limit the usable temperature ranges of these materials. Even if other substances with higher boiling points are used, the upper temperature limit for glass containers is soon reached, as all glasses soften at 600 to 800°C.

Bimetallic Thermometers. Two solids, say copper and iron, that have quite different expansion coefficients can be made to

[1] Helium has been solidified only at pressures greater than 22 times normal atmospheric pressure. In the course of magnetic experiments in enclosures surrounded by *liquid* helium, temperatures estimated to be within 0.0034°C of absolute zero have been attained.

serve as a thermometer if they are fastened together in the form of a "bimetallic" strip. When heated, the copper expands more than the iron, and the strip bends one way. When cooled, the copper contracts more, and the strip bends the other way. The

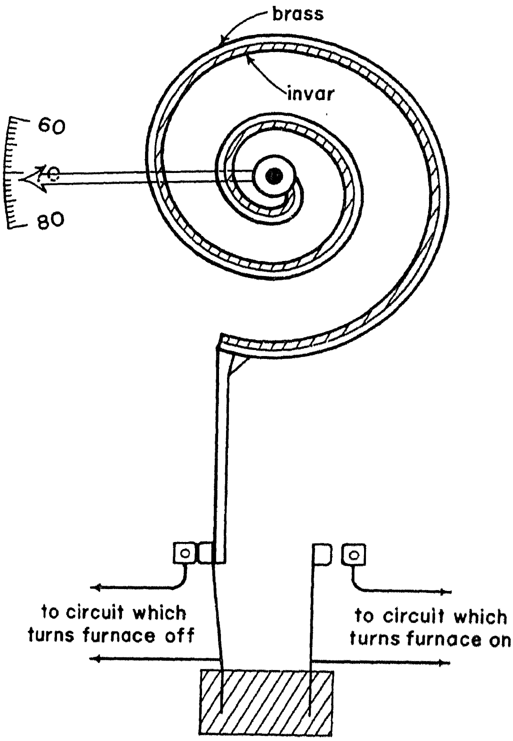


Fig. 150. Spiral bimetallic temperature control.

position of the end of the strip can be *calibrated* to measure the temperature. Often the strips are rolled into a spiral with the end geared to a pointer which indicates the temperature on a dial.

Although these devices are widely used for temperature measurement they are usually not very accurate. A bimetallic strip may be supplied with contacts so that it closes an electric circuit to a heater unit when the temperature falls below a fixed value, or so that it controls a refrigeration unit when the temperature rises too high. This is the arrangement of most automatic temperature controls.

Gas Thermometers. Almost any gas is a useful thermometric substance for temperatures above its condensation point. The

fractional change in volume per degree centigrade, which is just the volume expansion coefficient, is $\frac{1}{273}$ for any gas at temperatures sufficiently above its boiling point. This whole question of expansion of gases has many fundamental implications and deserves special consideration later (Chap. XII).

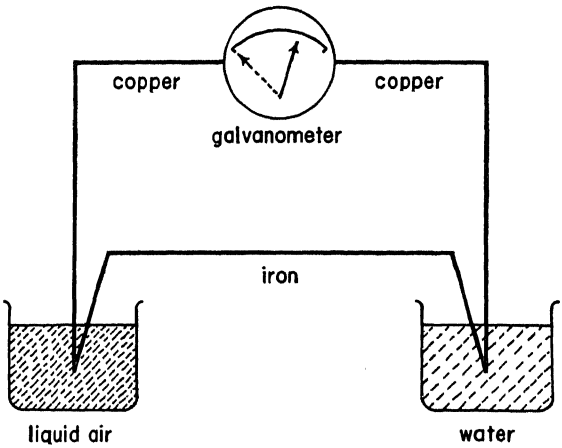
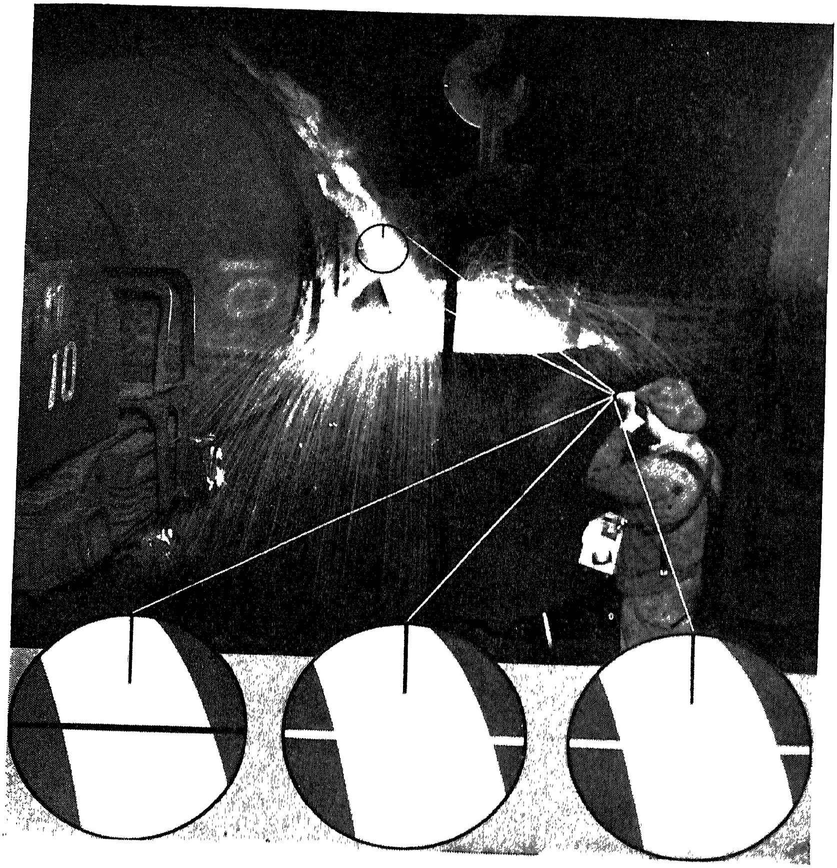


Fig. 151. Thermocouple.

Resistance Thermometers. The resistance of an electric conductor varies enough with temperature so that measurement of this resistance provides an excellent precision method of determining temperatures over a broad range. Platinum is widely used in resistance thermometers, for it remains solid below 1773°C. It is usable down to very low temperatures, to the point where a phenomenon known as ***superconductivity*** occurs. (As the temperature is reduced to a few degrees above absolute zero, many substances suddenly become almost perfect conductors.)

Thermocouples. When strips of two dissimilar metals such as copper and iron are joined at one end, and their other ends are connected to a galvanometer (a sensitive instrument for measuring electric current), a current is indicated if there is a temperature difference between the junction and the two ends at the galvanometer. This device is called a ***thermocouple.*** In spite of the fact that the origin of these ***thermoelectric*** currents is not entirely clear, thermocouples, often of special alloys, make convenient and excellent temperature measuring devices, usable over extensive temperature ranges.

Optical Pyrometers. Still other types of thermometers utilize optical principles for temperature measurement. The *optical pyrometer,* for example, compares the color of a hot glowing object with the color of a controlled hot filament in a lamp, and thus measures very high temperatures.



(*Leeds and Northrup.*)

Fig. 152. Measuring the temperature of molten steel with an optical pyrometer: Lower left: the temperature of the pyrometer filament is lower than that of the metal. Lower right: The temperature of the pyrometer filament is too high. Lower center: Correct adjustment for a temperature reading—filament and molten metal are at the same temperature.

Many people have shared the task of devising methods for measuring temperatures from near absolute zero to the highest obtainable temperatures. These measurements can now be made, in most cases quite easily, by using diverse properties of matter such as those which we have reviewed.

WHAT IS HEAT?

When mechanical energy is converted to heat energy by working against friction, the temperature rise in the heated object is found to be nearly proportional to the amount of energy transformed if no change of state occurs. Similar measurements lead to the further conclusion that to raise the temperature of 10 kg of water 1°C requires ten times as much heat energy as is used in raising the temperature of 1 kg of water 1°C. Thus, the change in heat energy of a body that does not change state is proportional both to the temperature change of the body and to its mass.

The temperature of a body in a fixed state, we have learned, is proportional to the average kinetic energy per molecule. Therefore, the heat energy of the body changes in proportion to the average molecular kinetic energy, and the heat energy would be completely removed only when all motion ceases, that is, at a temperature of absolute zero. Objects to which we add or subtract heat energy almost invariably already have much internal heat energy because their temperatures are ordinarily well above absolute zero. Because of our incomplete knowledge about the thermal behavior of bodies near absolute zero, we usually consider ***changes*** in heat energy rather than the total energy.

You might ask: If heat is energy, why not measure it in joules, or foot-pounds? Of course heat energy can be expressed in these units, but because the usual methods of measurement are not related to mechanical effects, a special more convenient unit of heat energy is ordinarily used.

Measuring Thermal Energy. In the metric system, changes in heat energy usually are expressed in ***kilocalories.*** For practical purposes one kilocalorie[1] (1 kcal) is the amount of heat energy that must be added to 1 kg of water to raise its temperature 1°C. In the English system, the unit of heat energy is the British thermal unit (BTU), which is the amount of heat required to increase the temperature of 1 lb of water 1°F. One BTU is equivalent to about 0.252 kcal. As the amount of energy required to heat 1 kg of water 1°C varies slightly between the freezing point and the boiling point, the kilocalorie is commonly defined at 15°C.

[1] Another metric unit, the calorie, is the amount of heat energy to raise the temperature of 1 g of water 1°C, *i.e.*, 1/1,000 of the kilocalorie.

Once the water is solidified to ice, or vaporized to steam, the corresponding quantity is changed greatly. For ice just below 0°C only about 0.5 kcal is needed to give a 1°C temperature rise to 1 kg, and, likewise, for steam above 100°C only about 0.5 kcal is needed.

Specific Heat. Water is quite unusual, for nearly every other substance requires much less heat per kilogram to raise its temperature the same amount. In order to express differences of this sort more accurately, we use the ***specific heat,*** which, in the metric system, is the number of kilocalories per kilogram required to change by 1°C the temperature of a material. This makes it possible to express very simply the change in heat energy of any object when its temperature is changed.

$$\text{Change in heat energy} = mS(T_2 - T_1) \text{ kcal}$$

Here m is the mass (in kilograms), S the specific heat of the object (in kilocalories per kilogram per degree centigrade), and T_2 and T_1 are the final and initial temperatures (in degrees centigrade).

The following table shows specific heats of some typical metals and of water under various conditions.

SPECIFIC HEATS

In kilocalories per kilogram per degree centigrade

Ice at 0°C	0.492	Lead at 20°C	0.031
Water at 0°C	1.0087	Silver at 20°C	0.056
Water at 5°C	1.0048	Copper at 20°C	0.092
Water at 15°C	1.0000	Iron at 20°C	0.107
Water at 30°C	0.9975	Aluminum at 20°C	0.214
Water at 100°C	1.0065	Lithium at 20°C	0.941
Steam at 100°C	0.482		

The high specific heat of water is important to man, for it means that a comparatively large amount of heat energy can be stored in water. This plays a great part in the control by oceans, lakes, and rivers of the climate of adjacent land bodies. We are familiar with the great climatic influence of warm ocean currents, such as the Gulf Stream as it flows along the Florida coast and eventually along the northern European coast. Furthermore, man makes use of the large amount of energy which can be stored in water for hot-water heating systems, and also in the generation of power. Likewise, it is useful for cooling, refrigeration, and air-conditioning installations.

Conservation of Heat Energy—Calorimetry. We expect the temperature of hot coffee to fall when cream is added to it. Can we go further and predict the temperature of the mixture if we know enough about the properties of the cream and coffee? To make this prediction, we must again call upon the law of conservation of energy, and this time apply it to the exchange of heat energy. If we mix a number of substances that have different temperatures they will eventually come to a common temperature between that of the hottest substance and the coldest, but if the mixture is properly insulated the amount of heat energy lost by the hotter substances must be equal to the amount gained by the colder.

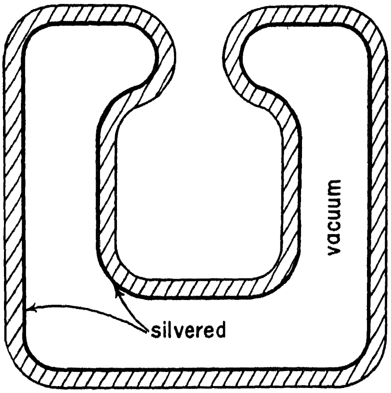


Fig. 153. Dewar Flask—schematic.

Careful experiments of this type are usually performed inside of a container called a *calorimeter* which is carefully designed and insulated so that the heat loss or gain from the surroundings is very small. One of the best types of calorimeter from this standpoint is the so-called Thermos bottle, often called "Dewar flask," after Dewar, the Scottish physicist who developed it. These bottles are made by evacuating the space between two containers one of which is within the other. Heat conduction is minimized by the absence of air or other material between the inner and outer parts, and transfer of heat by radiation is made small by "silvering" the walls so that radiation from either the inside or the outside is reflected back to the side from which it came.

Suppose that we want to measure the specific heat of iron. If a calorimeter of mass m_c contains m_w grams of water at a temperature T_1, and we drop into it a mass m_I of iron at a high temperature T_2, then the mixture will come to some final temperature T_3 (see Fig. 154). Since the total energy must be unchanged, we can say:

Heat lost by iron = heat gained by water
+ heat gained by calorimeter

or

$$m_I s_I(T_2 - T_3) = m_w s_w(T_3 - T_1) + m_c s_c(T_3 - T_1)$$

where s_I, s_w, and s_c are the respective specific heats of the iron, water, and calorimeter. Of these quantities, $s_w = 1$ kcal/kg/°C, of course, and the masses and temperatures are measured easily. If the calorimeter is made of some known material, its specific heat

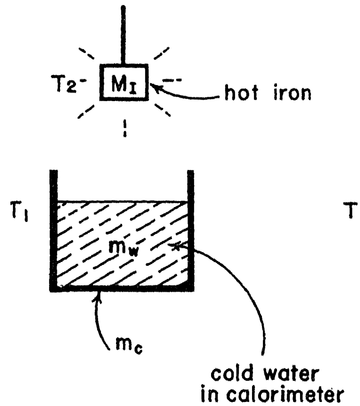


Fig. 154. The heat lost by the iron is gained by the water and calorimeter cup.

s_c can be found in standard tables. This leaves only a simple computation in order to find s_I, the specific heat of the iron. The high specific heat of water is illustrated graphically when such an experiment is performed, for even if the iron be at red heat (above 500°C) the temperature of an equal mass of water rises only about 50°C.

Heats of Fusion and Vaporization. Some additional very important changes in heat energy occur when substances undergo ***changes of state,*** that is, when they melt or boil, or when they freeze or condense.

Suppose, for example, that we start with 0.1 kg of very cold ice, say at −40°C, place it in a beaker on an electric heater, and watch its temperature as heat energy is supplied to it at a steady rate.

The temperature is seen to rise steadily until 0°C is reached. Then, if there is careful stirring, it remains constant until all the ice is melted. After this, until 100°C is reached, the temperature rises steadily but only about half as rapidly as when the water was ice, and it stays at 100°C until all the water is evaporated. If we could have caught the steam and kept it under constant pressure, its temperature would have continued to rise steadily again. This experiment shows clearly that large amounts of heat energy must be provided to convert a solid to a liquid or a liquid to a gas.

The energy required to melt one kilogram of a substance at its melting temperature is called its ***heat of fusion.*** Similarly, the energy required to evaporate one kilogram of a substance at its boiling point is called its ***heat of vaporization.*** The heat of vaporiza-

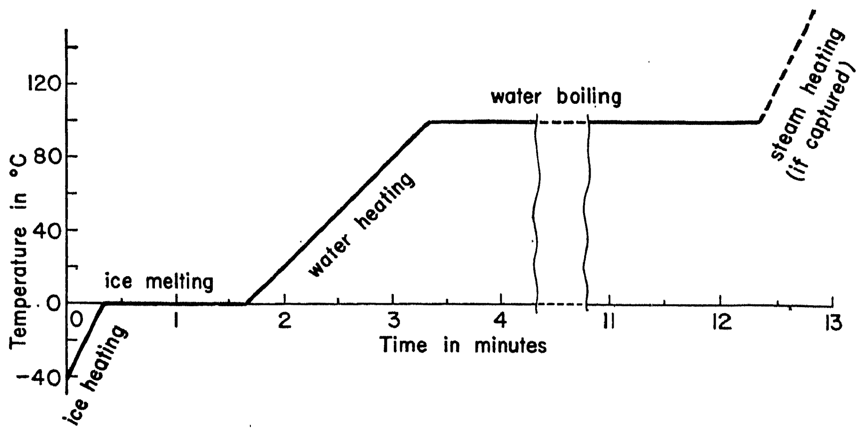


Fig. 155. Heating curve of 0.1 kg of water initially at −40°C. Heat is added at the rate of 6 kcal/min. Note that ice and steam rise in temperature twice as rapidly as liquid water; hence their specific heat is half as great.

tion, especially, depends on pressure and it is usually specified at normal atmospheric pressure. Naturally, in order to reverse the process and condense a gas to a liquid, or freeze a liquid to a solid, it is necessary to ***remove*** from the substance exactly these same amounts of energy which were required for melting it or evaporating it.

Now let us find the total energy required to boil away the 0.1 kg of ice at −40°C with which we started. Since the specific heat of ice is about 0.5 kcal/kg/°C, for heating 0.1 kg of ice from −40°C to 0°C, we need

$$(0.1\text{ kg}) \times (0.5\text{ kcal/kg/0°C}) \times (40°\text{C}) = 2\text{ kcal}$$

The heat of fusion of ice is 80 kcal/kg, so to convert 0.1 kg of ice at 0°C to water at 0°C, the heat energy required will be

$$(0.1\text{ kg}) \times (80\text{ kcal/kg}) = 8\text{ kcal}$$

Since the specific heat of water is 1 kcal/kg/°C, to raise the temperature of 0.1 kg of water from 0°C to 100°C will require

$$(0.1\text{kg}) \times (1\text{ kcal/kg/°C}) \times (100°\text{C}) = 10\text{ kcal}$$

Finally, the heat of vaporization of water is 540 kcal/kg, so the heat energy needed to convert 0.1 kg of water at 100°C to steam at the same temperature is

$$(0.1 \text{ kg}) \times (540 \text{ kcal/kg}) = 54 \text{ kcal}$$

In boiling away the ice, then, the energies corresponding to the various sections of the curve of Fig. 155 total

$$(2 + 8 + 10 + 54) \text{ kcal} = 74 \text{ kcal}$$

The large amount of energy associated with changes of state make such changes very important and often very useful to man. The high energy content of steam, for example, is particularly advantageous for many applications such as steam heating or the operation of steam engines.

In general, all substances behave much the same when changing state, although the temperatures at which the states change and the accompanying energy changes differ. Later we shall see that such energy changes are just of the sort that we should expect when the molecules must be made progressively freer as the substances passes from solid to liquid, or from liquid to gas.

Conversion of Mechanical Energy to Heat Energy. The dramatic experiments of Count Rumford first showed clearly that mechanical energy could be converted into heat energy. About 1800 Sir Humphry Davy (1778–1829) demonstrated this even more strikingly when, by rubbing together two pieces of ice in vacuum, he generated sufficient heat to melt the ice. It remained for James Prescott Joule (1818–1889), in the course of years of careful investigation, to show conclusively that no matter how mechanical work is done—by moving paddles in water, forcing liquids through pipes, turning electric generators to produce heat in resistances, rubbing metals together, etc.—the ratio of the mechanical energy input to the heat energy output is always the same.

Modern measurements give 4,186 ***joules*** (newton-meters) of mechanical energy as equivalent to 1 ***kilocalorie*** of heat energy —almost the same as the value obtained by Joule. This ratio is called the ***mechanical equivalent of heat.*** In other words, the work done in lifting a mass of 1 kg a vertical distance of about 400 meters (nearly ¼ mile) would, if converted into heat, be only enough to increase by 1°C the temperature of 1 kg, or about 1

quart, of water. This is a considerable amount of work—equivalent to that done by a 150-lb man in climbing almost two flights of stairs.

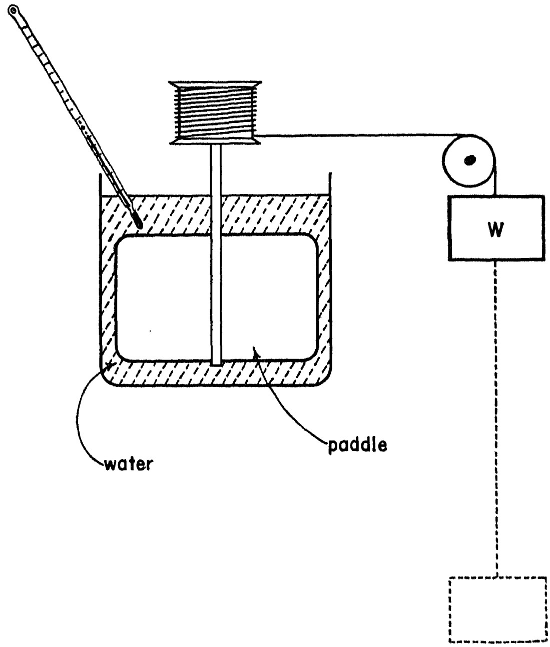


Fig. 156. Mechanical to heat energy. Simplified version of Joule's apparatus. The falling weight turns the paddle, thus raising the temperature of the water.

In the English system of units, 778 ft-lb equals 1 BTU; so in summary

$$4{,}186 \text{ joules} = 1 \text{ kcal}$$
$$778 \text{ ft-lb} = 1 \text{ BTU}$$

Wherever there is motion we see the process of conversion of mechanical energy into heat energy. In fact, the conversion is much too easy. In this industrial age, small wonder that a great deal of effort is spent in reducing friction in machines.

Heat Engines. What about the reverse process? Can we convert heat energy into mechanical energy? Certainly it is possible, because this process is the source of much of our present-day power. Our steam engines and turbines, our gasoline or Diesel internal-combustion engines, are ***heat engines***. All make use of the conver-

sion of the chemical energy in coal or petroleum compounds into heat energy, and the conversion of the heat energy in turn into mechanical energy. These engines along with water-power devices are the "prime movers" in our industrial system. We shall reserve the details of the entertaining subject of heat engines for Chap. XIV.

FUELS—CHEMICAL ENERGY

Chemical Energy in Use. The chemical combination of oxygen and materials such as coal and petroleum products is, with the exception of water power, the immediate source of practically all energy that we use today. The chemical energy from these compounds, either directly or indirectly, after transformation to electric energy, serves to heat our houses, to propel our motor cars, trains, and ships, and to operate mills and the other machines of industry. Most of the energy we use came originally from the sun as light and was changed to chemical energy and stored by plant life. Through long ages the remains of plants, and of animals which fed on the plants, accumulated and were acted upon by the heat and pressure that accompanied geological changes. The results were coal, oil shale, petroleum, and natural gas. These are carbon, or ***hydrocarbon*** compounds which contain principally carbon and hydrogen in chemical combination. The coal and carbon compounds that have accumulated in the earth and in the cellulose of wood and other plant products provide most of the chemically stored energy which we use through combustion.

Liberation of Chemical Energy. Chemical reactions which produce new compounds from a mixture of elements or other compounds are, as pointed out before, either ***endothermic*** or ***exothermic;*** either they absorb energy or else energy is evolved. Most chemical reactions are reversible; for example, if energy is liberated by the combustion of a compound (by its combination with oxygen), then the addition of energy to the products of combustion under the proper conditions will re-form the original compound.

One of the simplest fuels is hydrogen gas. When hydrogen combines with oxygen to form water, energy is liberated, and the chemist writes a simple equation to describe this process

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat energy}$$

If two ***gram-molecular weights*** of hydrogen and one of oxygen are

used, that is, 4 g of hydrogen (twice the molecular weight of H_2), and 32 g of oxygen (the molecular weight of O_2), then 36 g of water are produced, and measurements show that 138 kcal of energy are liberated. This union of hydrogen and oxygen gives one of the

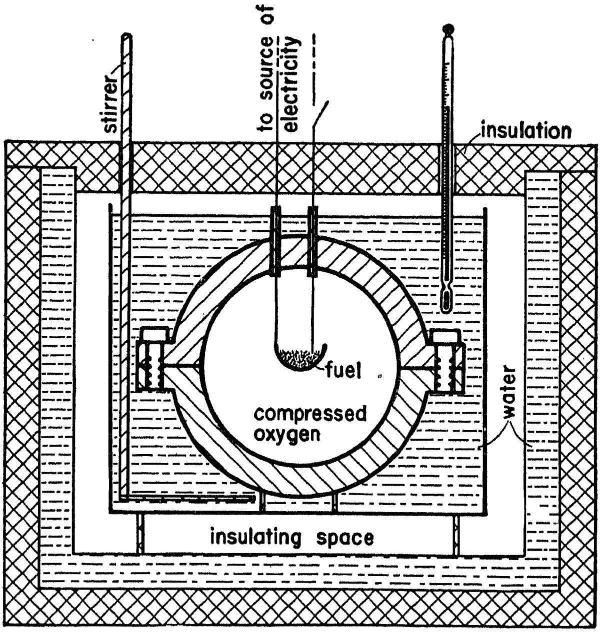


Fig. 157. Simple "bomb" calorimeter. The fuel is ignited by an electric spark. The heat energy released is obtained from the temperature rise of the water in which the "bomb" is immersed.

hottest flames known, and is used in the oxyhydrogen torches for welding structural steels.

Measuring Chemical Energy. The quantity of heat energy liberated in a chemical reaction may be determined by placing known amounts of the materials in a calorimeter and measuring the rise in temperature and hence the number of calories of heat produced when a reaction takes place. When substances unite with explosive violence, and when gases are evolved, strong sealed "bomb" calorimeters must be used. When the heats of combustion of gases like natural gas or ordinary illuminating gas are measured, a known amount of the gas is usually burned in such a way that practically all the heat is absorbed in a known quantity of water. The energy content of the gas in kilocalories per cubic meter or BTU per cubic foot can then be determined.

By means of a calorimeter, we can measure the difference in energy before and after a reaction such as the combination of hydrogen and oxygen to form water. We find that energy is liberated, so the energy stored in two H_2 molecules, and one O_2 molecule

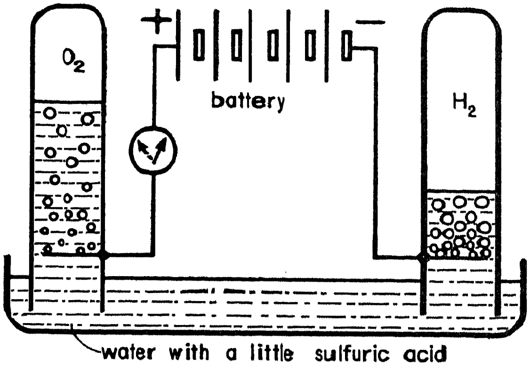


Fig. 158. Electrolysis of water. When H_2O is decomposed, the volume of hydrogen is twice the volume of oxygen (at the same temperature and pressure).

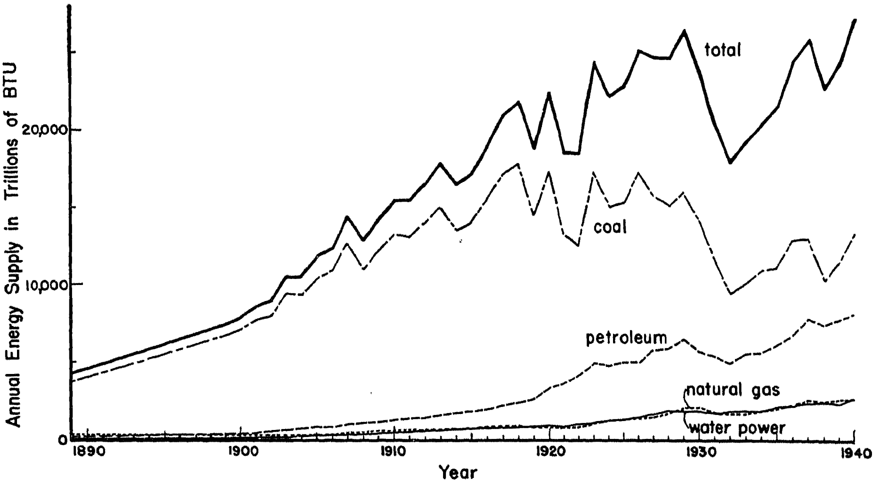
must be more than the energy stored after they have combined as two molecules of water (H_2O). This energy must be stored as potential energy involving forces between the atoms within the molecules.

Conversion of Heat into Chemical Energy. Just as mechanical energy and heat energy can be interconverted, heat energy and chemical energy can be converted, each into the other. Suppose, for example, that we investigate the decomposition of water, the reaction which is the reverse of combining hydrogen and oxygen. Then we find that this reaction can be accomplished if energy is ***added*** and the conditions are otherwise suitable. The process would be described

$$\text{Energy} + 2H_2O \rightarrow 2H_2 + O_2$$

The energy needed to change two H_2O molecules into two H_2 molecules and one O_2 molecule, that is, to put hydrogen and oxygen back into the original free state, is equal to the energy liberated when the free molecules combine to form water. One of the most convenient ways of producing hydrogen and oxygen commercially is to separate water into its constituents by using electric energy. When an electric current is passed through water by means of electrodes attached to a source of electric energy, H_2 gas is liberated

at the negative electrode and O_2 gas at the positive. This method is used to produce most of the hydrogen and oxygen supplied under pressure in steel tanks for welding and for all sorts of industrial, physical, and chemical uses.



(*Data chiefly from Minerals Yearbooks, U.S. Bureau of Mines, Washington, D.C.*)

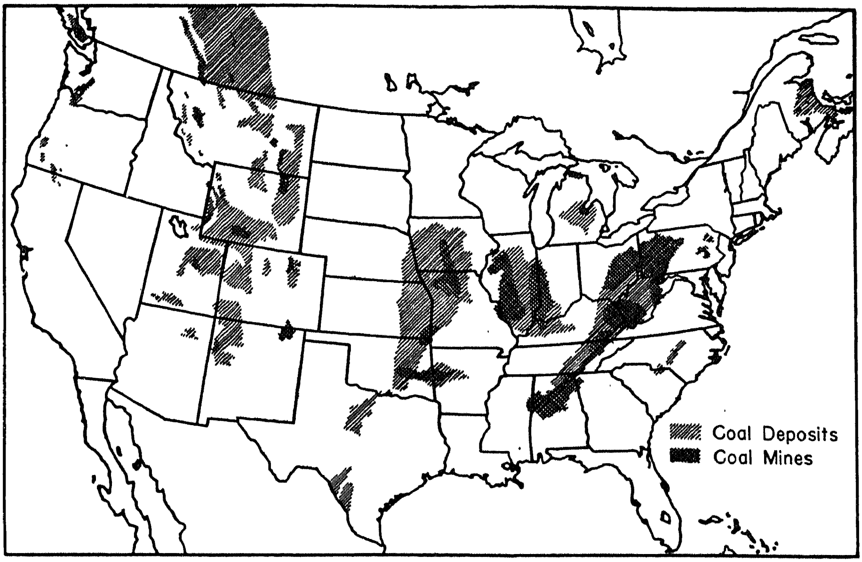
Fig. 159. Annual supply of energy from mineral fuels and water power in the United States.

Transformations of chemical energy into heat energy, and of heat or electric energy into chemical energy, illustrate again the fact that the different forms of energy are really equivalent as far as the application of the law of conservation of energy is concerned.

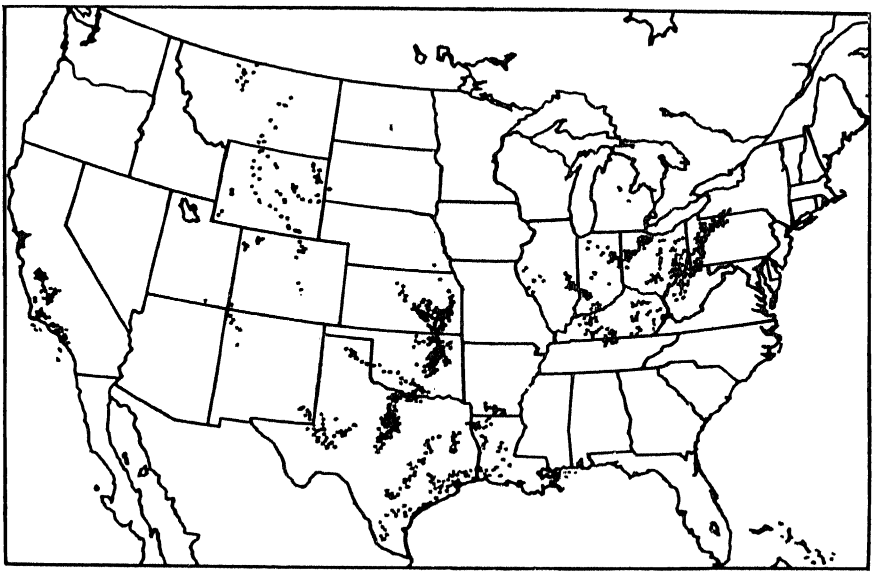
The Conservation of Natural Fuels. The use of coal and petroleum and natural gas as sources of heat energy is increasing continually. Since these materials represent some of our major natural resources, their intelligent use and conservation is a serious world-wide problem.

Although men learned early in history that certain "black stones" would burn, and have been using them for fuel ever since, the visible supply of coal of today appears to be sufficient for many centuries.

Edwin Drake first succeeded in drilling a well for oil in Pennsylvania in 1859. Since then uses for this liquid wealth have multiplied constantly. In the United States alone over 70 billion gallons of petroleum are used each year—considerably more than in all the



(a) Coal deposits and coal producing regions in the United States.



(b) Oil fields of the United States.
Fig. 160.

rest of the world. Great fortunes have been won in the marvelous development of oil production, refining, and distribution systems, and at the same time prodigious wastes have occurred. War requirements for petroleum products are enormous—for ships, planes, and mechanized armies. New types of bombers have gasoline tanks of 20,000 gallons capacity!

The extent of the petroleum supply is not certain. So far, discoveries of new oil fields, recently aided by so-called ***geophysical*** methods for locating oil deposits far underground, have more than kept pace with the increasing use of oil. At present the deepest oil wells are only about three miles down, but oil strata surely exist many miles deeper in the earth's crust. Well-drilling techniques are continually being developed to go farther into these lower lying strata. It is quite certain that recurring predictions that our oil supplies will last only another ten years are unfounded, as the present apparent supply is more than twenty times the present yearly consumption. However, it is equally true that these supplies have a definite limit, and must eventually become exhausted, at least from the standpoint of economical production.

This suggests the development of substitutes for natural petroleum products, or the building of these products from quite different compounds. The production of oil and gasoline from coal has already been developed abroad. The use of synthetic fuels from plants, such as alcohol, also has practical possibilities; in fact, the mixing of alcohol with gasoline is already prescribed in several countries. Because of their high production cost, such synthetic fuels have not yet been put into wide use in this country, where petroleum is still plentiful and is not taxed entirely beyond reason. Eventually, however, new sources of energy must be found for the future.

FOR STUDY AND READING

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SUMMARY

Count Rumford concluded that heat is a sort of internal motion, and we now know it to be the energy of molecular motion.

The temperature of matter is proportional to the average molecular kinetic energy. Absolute zero ($-273.16°C$) is the temperature at which there would be no molecular motion.

Temperatures on earth extend from below $-272.2°C$, the melting point of helium, to 6440°C, the temperature in a tungsten arc. Ordinary mercury and alcohol thermometers are limited by boiling and freezing of the liquids. Other types of thermometers are: bimetallic strips, also used for automatic temperature controls, gas thermometers, resistance thermometers, thermocouples, and optical pyrometers.

The change of heat energy of a body that does not change state is proportional both to the temperature change of the body and to its mass. The ***kilocalorie*** is the quantity of heat energy that will change by 1°C the temperature of 1 kg of water at 15°C. The ***British thermal unit*** (BTU) is the amount of heat energy required to increase by 1°F the temperature of 1 lb of water. The ***specific heat*** of a substance is, in the metric system, the number of kilocalories per kilogram required to change by 1°C the temperature of the substance. Thus, for any object which changes temperature without change in state

$$\text{Change in heat energy} = \text{mass} \times \text{specific heat} \times \text{temperature change}$$

When substances at different temperatures are mixed, the heat energy lost by the hotter substances just equals that gained by the colder ones—that is, heat energy is conserved. For measurement, the mixture is insulated by a container called a ***calorimeter.***

Heat of fusion (or ***heat of vaporization***) of a substance is the heat energy needed to melt (or evaporate) 1 kg of the substance at NP and at its melting point (or boiling point). The unit of heat of fusion or vaporization is the kilocalorie per kilogram.

Measurements on the conversion of mechanical energy to heat energy show

$$4{,}186 \text{ joules} = 1 \text{ kilocalorie}$$
$$778 \text{ ft-lb} = 1 \text{ BTU}$$

Heat engines make use of the reverse process, the conversion of heat energy to mechanical energy.

Excepting water power, nearly all of the energy we use comes from carbon or hydrocarbon compounds such as coal and petro-

leum. The heat energy liberated in a chemical reaction may be measured in calorimeters of various types. Most exothermic chemical reactions may be made to reverse so that heat energy will be stored as chemical energy.

The limited supply of natural fuels emphasizes the need for conservation and for development of new fuels.

QUESTIONS

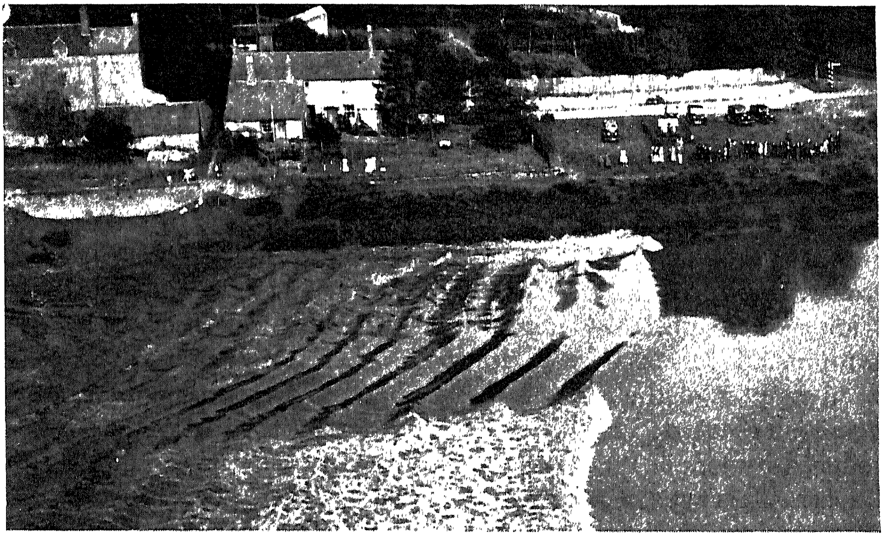
1. Why has it been customary to measure heat energy in units different from those used for mechanical energy?
2. Do we have any basis for considering the ***temperature*** of a substance as fundamentally associated with the average kinetic energy of the molecules of the material?
3. What types of physical phenomena are suitable for measuring temperature? Is the expansion of a substance like mercury necessarily the most accurate basis for thermometry?
4. How do we use the ***kilocalorie,*** or ***British thermal unit,*** in the measurement of heat energy?
5. How is the principle of conservation of energy applied to measurements concerning heat transfers?
6. What is the basic law of heat change where there is no change of state?
7. If 0.050 kg of alcohol at 30°C (specific heat 0.65 kcal/kg/°C) is added to 0.200 kg of water at 5°C, what will be the temperature of the mixture?
8. In what way do changes of state influence changes in heat energy?
9. How much heat energy is required to obtain 1 kg of boiling water from ice at −20°C? (Neglect heat losses and evaporation.)
10. 0.010 kg of steam at NP is condensed in 0.200 kg of water which was initially at 20°C. If the water is in a 0.100-kg calorimeter cup that has a specific heat of 0.092 kcal/kg/°C, what should be the final temperature?
11. What was the importance of the experiments of Rumford and Joule which disproved the caloric theory of heat and proved that a definite amount of mechanical energy is equivalent to a definite amount of heat energy?
12. If each day a man eats food with a fuel value of 3,000 kcal and does 1,500,000 joules of useful work, what is his efficiency?
13. What processes do we know that involve or depend on transfers of mechanical energy to heat energy, or the reverse? What about heat engines?
14. Do chemical reactions always involve changes in energy?
15. What happens to the energy (usually heat) absorbed or liberated in chemical reactions?
16. Can we say that energy is conserved in the combustion of coal, gas, or gasoline?
17. Of what chemical reactions do we utilize the energy on a large scale, either directly or indirectly?

CHAPTER VIII

ENERGY IN WAVES

TRANSPORTING ENERGY BY WAVES

Most of our knowledge of nature comes from energy brought to us by waves of sound and light. Moreover, practically all the energy with which we do work was initially carried to the earth by waves streaming from the sun. What is the nature of these intangible waves which are capable of transporting energy?



(*Brown Photos.*)

Fig. 161. Tidal wave from the sea sweeping along the River Severn.

Water Waves. Surely everyone has dropped a stone into a quiet pool and after the splash watched the ringlike ripples travel outward in ever-widening but ever-fainter concentric circles. On a very different scale are the long rolling waves which, in calm weather, seem to beat an endless rhythm as they break on a sandy beach. When the ocean is whipped by high winds, huge waves fifty feet or

more in height carry tremendous energy enabling them to smash buildings and breakwaters along the shore front and to toss and batter even the largest ships. Although these manifestations have intrigued most of us, the combination of circular and to and fro

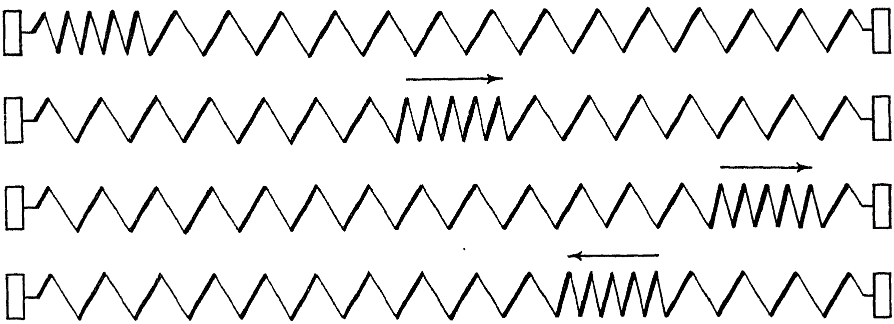


Fig. 162. Compressed region traveling along a spring and being reflected at the far end.

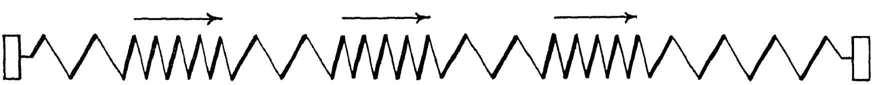


Fig. 163. A series of compressed regions traveling along a spring.

motion in water waves is quite involved, so let us use a simpler example to show the general characteristics of wave motion.

Motion in Waves. Longitudinal Waves. The process of setting up waves can be shown easily with a stretched coil spring. Suppose that we compress a small section of the spring near one end, thus adding to the spring's potential energy. When released, the single compressed region travels down the spring, is *reflected* by the fixed support at the far end, travels back to its starting point, and again is reflected. This continues until finally the disturbance is so reduced by loss of its energy through friction that it can no longer be seen. This type of wave motion is called *longitudinal* because the compression of the spring is along the direction in which the disturbance moves.

If the end of the spring is compressed and released several times in rapid succession, the train of alternate compressed and expanded regions travels along the spring and also is reflected at the ends, the size of each disturbance diminishing as the train progresses.

Standing Waves. If the spring is continually compressed and expanded at the proper rate, say by a motor-driven device, the compressions and expansions traveling down the spring in one

direction meet those already reflected from the end beyond. The two waves *interfere* with each other (that is, they combine), canceling one another at some positions and reinforcing at others, so that a *stationary wave* or *standing wave pattern* is produced which to

Fig. 164. Longitudinal "standing wave" on a spring.

the eye does not appear to progress. When a so-called stationary wave on a spring is illuminated by a strong light that flashes on and off at the proper rate, the individual compressions and expansions appear to travel along the spring and be reflected just as before. With this light one can make the disturbances appear to move slowly or even to "stand still" so that they can easily be observed in detail. Such a flashing light, called a *stroboscope,* is very useful for analyzing all sorts of recurrent motion.

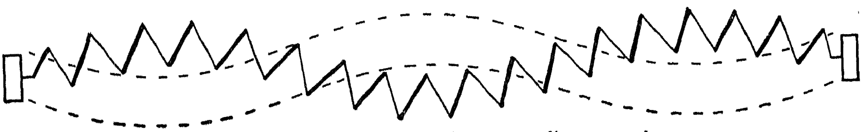


Fig. 165. Transverse "standing waves" on a spring.

Reflection and interference, as illustrated by waves on a spring, are observed with all other types of wave. In fact, they are so characteristic of wave motion that the association of both of them with any type of energy transfer is immediately taken to show that it is a form of wave motion.

Transverse Waves. If, instead of being compressed, the coiled spring is pulled to the side and then released, transverse waves are produced. Here the motion of any part of the spring is perpendicular to the direction in which the disturbance progresses, so this is called a *transverse* wave motion. Light behaves like transverse waves.

Sound Energy. Sound waves in air are of the longitudinal type of wave motion. The air, which is highly elastic, plays the role of the coiled spring. A *medium* is necessary in which to transfer sound energy. Any doubt about this can be dispelled by listening to an electric bell placed inside a container that can be evacuated. The ringing of the bell can be heard clearly when there is air in the

container, but as the air is pumped out it gradually becomes fainter and finally, when the air is largely removed, it cannot be heard at all.

A tuning fork with prongs moving back and forth, or a bowed

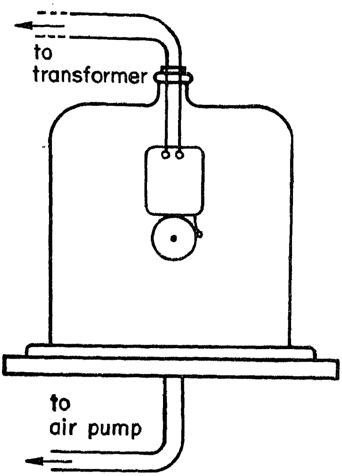
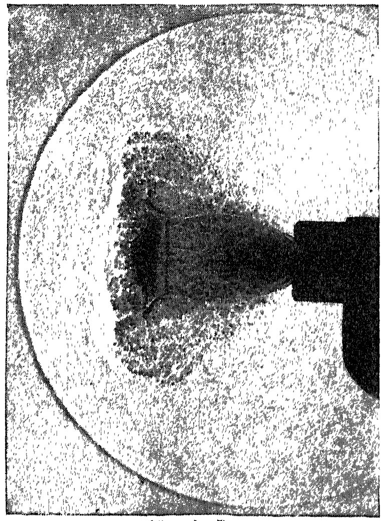


Fig. 166. A ringing bell cannot be heard when the surrounding air is removed.



(*Quayle, Bureau of Standards.*)

Fig. 167. Sound wave front from a revolver which has just been fired. Photograph of single flash of light from spark.

violin string over a sounding board, alternately compresses and expands the air as it vibrates. The successive regions of high and low pressure travel outward from the source in all directions. Does this imply that a current of air moves whenever sound is transmitted? Not at all. Each molecule simply vibrates back and forth, pressing and pulling on its neighbors and so transferring its energy of vibration onward. Sound energy, then, is usually transported as a vibration of the molecules of the air. This is why we say that air is the ***medium*** that serves to transfer sound energy.

Sound travels through air at ordinary temperatures with about the speed of a bullet from a low-power rifle, about 1,100 ft/sec or 330 meters/sec. Its speed decreases somewhat when the air is colder. An interval of 10 sec between seeing a lightning flash and hearing the thunder associated with it means that the lightning must have struck about two miles away. The lightning is seen almost immediately, because light waves travel with a speed of 186,000 miles/sec or 3.00×10^8 meters/sec, and the delay is prac-

tically the time required for the sound to travel from the lightning to the observer.

Sound waves travel much faster in liquids and solids than in air. They have speeds of about 4,800 ft/sec in water and nearly 16,000 ft/sec in steel. It is the change of velocity of a wave in passing from one medium to another that produces refraction. This phenomenon was introduced to us for light waves in the description of optical properties of matter (Chap. IV). We recall that the refraction of a wave is simply the change in direction of travel of the wave when it passes obliquely through a surface separating two different media.

OF VIBRATING THINGS

Human voices, each characteristic of an individual, the distinctive sounds produced by the various instruments in a symphony orchestra, in fact all the sounds we hear, are initiated by vibrating things. Since they influence us so greatly, let us learn what we can about vibrating objects and the way in which they produce sound waves.

Everything in nature is somewhat elastic and will vibrate to a certain extent when deformed and released; the nature of the vibration depends on the elastic properties of the vibrating body. Consequently our inquiry into vibrating objects might well start with Hooke's law, which, as we recall, states that the force F which an object exerts as the result of an elastic deformation, is proportional to the deformation x, or, in compact form: $F = kx$. Here k is the elastic constant of the particular object, the force per unit deformation. Suppose that we attach an object of mass m to a coil spring, and that the spring stretches a distance x so that the mass is at some position represented by A in Fig. 168. According to Hooke's law

$$F = mg = kx$$

Now if the mass m is pulled down still farther to position B, potential energy is added to the spring, and when the mass is released it moves toward position A. However, when it reaches A it has kinetic energy, so it "overshoots" and goes up to C before the kinetic energy is transformed back into potential energy and the mass stops momentarily. From C it accelerates downward, gains kinetic energy, overshoots A once more, and continues

oscillating in this manner. Like the pendulum, it vibrates about the zero or equilibrium position A with gradually decreasing peak displacement or ***amplitude*** until finally air resistance and other friction bring it to rest.

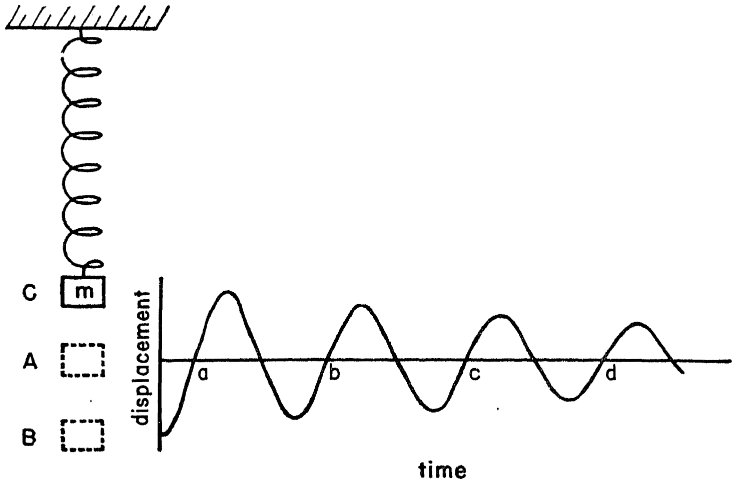


Fig. 168. Vibration of mass on spring.

Simple Harmonic Motion. If the amplitude were constant, such simple, regular vibrations in which the restoring force is proportional to the displacement would be called ***simple harmonic motion.*** When the amplitude of the vibration gradually decreases because of frictional losses, the motion is said to be ***damped*** simple harmonic motion. This latter is the simplest form of motion that a freely vibrating body actually may have, as some damping always exists.

Frequency and Period. Just as with the pendulum, the time required for one complete vibration is called the ***period.*** It is the same no matter how large the swing so long as the character of the motion does not change. The period is represented by the time *ab*, *bc*, or *cd* in Fig. 168.

The number of complete vibrations, or "cycles," per second is the ***frequency.*** The frequency is clearly just the inverse of the period; that is

$$\text{Frequency} = \frac{1}{\text{period}}$$

The frequency is often referred to as so many "cycles per second."

Every vibrating body has at least one ***characteristic frequency*** of vibration which should depend in some way on its mass and on

its elasticity. Take, for example, the coil spring with the attached mass. Experimentally one finds that if the mass is increased four

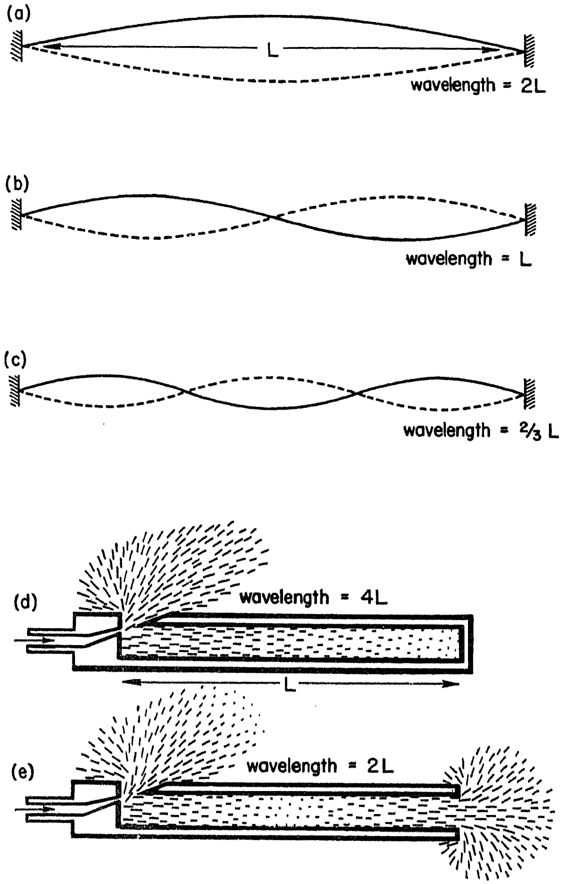


Fig. 169. Vibrating objects. Most systems may vibrate in numerous ways. (a) The fundamental vibration (of greatest wave length) of a string has a wave length twice the length of the string; (b) the first overtone has a wave length equal to the length of the string; and (c) the second overtone has a wave length two-thirds the length of the string, etc. The positions of maximum motion are often called loops and those of minimum motion nodes. (d) The wave length of the fundamental vibration of a closed organ pipe is four times the length of the pipe; and (e) that of an open pipe is twice the length of the pipe. (The longest dashes within the pipe indicate positions of maximum motion of air molecules due to the standing sound waves—loops—and the dots indicate positions of least motion—nodes.)

times, the frequency is reduced by a factor of $\frac{1}{2}$; if the mass is doubled the frequency is reduced by $1/\sqrt{2}$, and so on. So the frequency is inversely proportional to $\sqrt{m}$. If the spring is made

four times as stiff, that is, if k is made four times as large, the frequency is doubled; if k is doubled the frequency is increased by $\sqrt{2}$, and so on. So the frequency is proportional to $\sqrt{k}$. In fact, careful measurements show that the complete expression for the characteristic frequency in terms of m and k is

$$\text{Frequency} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The frequency will be in cycles per second if k is in newtons per meter and m is in kilograms.

There is a similar expression for frequency of vibration of any sort of elastic body that is deformed and released, a string on a piano, violin, or guitar, the head of a bass drum, a carillon bell, etc., even to the steel framework of a new building when it receives the blows of a riveter's compressed air hammer. In an organ pipe or in any other wind instrument, the vibrations are set up in the column of air inside the instrument itself. The characteristic frequency of vibration in these latter cases is inversely proportional to the length of the vibrating air column. Indeed, we shall meet characteristic frequencies in many phenomena, even as far afield as in electric circuits, especially those applied to radio.

Resonance. The frequency at which a pendulum swings when disturbed or the frequency of vibration of an organ pipe when it is sounded is just the natural or characteristic frequency of the pendulum or of the organ pipe. When two organ pipes of the same dimensions are near one another, if one is sounded, the other will commence to vibrate as a result of the small amount of energy transferred to it through the air. A much larger amount of energy applied at a frequency slightly different from the natural frequency of the pipe would produce no such response. This magnified response of any vibrator at its characteristic frequency is called ***resonance.*** The reason that there can be resonance is seen by considering the pendulum. Small taps on a pendulum each time it reaches the end of a swing (in other words, taps applied with the natural frequency of the pendulum) build up large swings, because every tap gives a boost in the direction of the motion—the same effect as a child "pumping" his swing. On the other hand, if they are applied at a slightly different rate, some of the taps retard the

motion and some aid it so that the two effects cancel one another after sufficient time.

Resonance is a most important effect which extends to all vibrating or "periodic" systems—mechanical systems, electric circuits, atoms absorbing light vibrations, etc.

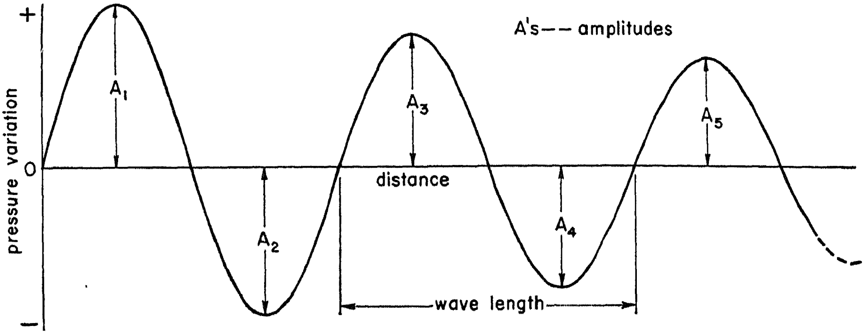


Fig. 170. Diagram of sound wave at some instant.

Ideas about Waves. When a string or other vibrating object alternately compresses and rarefies the air adjacent to it, the resulting high- and low-pressure disturbances travel outward as a "sound" wave. At any instant the pressure variations, or the displacements of the molecules due to the sound wave, might be distributed at various distances away from the source as shown in Fig. 170. In this case, the amplitude is the peak variation from the average pressure of the pressure associated with the sound vibration.

Frequency and Wave Length. The distance between successive similar points in a series of waves, that is, points which have the same "phase," is called the ***wave length.*** This is illustrated in Fig. 170. If a source of sound is emitting waves of some particular frequency, the faster the wave travels, the greater the wave length. Conversely, the more vibrations per second, the shorter the distance between successive waves for a fixed velocity. To be more specific

$$\text{Wave length} = \frac{\text{speed of wave}}{\text{frequency}}$$

This fundamental relation is true for all kinds of waves, sound waves, light waves, radio waves, etc.

When you strike middle C on a piano the sound frequency is 258.7 vibrations per second, the speed of sound waves is about 1,100 ft/sec in air, and so the wave length is given by

$$\text{Wave length} = \frac{1{,}100 \text{ ft/sec}}{258.7\text{/sec}} = 4.25 \text{ ft (approximately)}$$

When radio station WEAF broadcasts, the frequency of alternation of the high-frequency currents in the station's antenna is 660 kilocycles/sec or 660,000 cycles/sec. Radio waves, like visible light waves, travel with a speed of 186,000 miles/sec or 3×10^8 meters/sec in air, and only a tiny fraction faster in a good vacuum. The length of the radio wave from WEAF is then

$$\text{Wave length} = \frac{3 \times 10^8 \text{ meters/sec}}{660{,}000\text{/sec}} = 454 \text{ meters (or about 1490 ft)}$$

Wave Intensity Decreases Rapidly with Distance. The sun, like most other sources of wave energy, radiates its energy uniformly in all directions. What, for example, is the relation between the energy falling on the earth and on Jupiter? Figure 84, page 117, has already helped us to answer this question. The energy travels in approximately straight lines from its source, so the total amount of energy passing each second through the areas A, B, and C is the same provided there is no absorption in the medium. Since these areas are in the proportions 1^2, 2^2, and 3^2, it follows that the intensity or the amount of energy per second falling on a unit area is inversely proportional to the square of the distance from the source. That is

$$\text{Intensity} \propto \frac{1}{d^2}$$

where d is the distance from the energy source, the sun in this case.

Now we can answer our question about the earth and Jupiter. Jupiter is about 5.2 times farther from the sun than is the earth, so the light intensity on Jupiter is $1/(5.2)^2$ or $\frac{1}{27}$ as great as on earth. However, Jupiter's diameter is about 11 times greater than the earth's, so its disk facing the sun is $(11)^2$ or 121 times that of the earth. Hence the total light energy falling on Jupiter each second (that is, the *power*) is $\frac{121}{27}$ or about $4\frac{1}{2}$ times as much as reaches the earth.

The ***inverse square law*** applies to all types of wave energy, to radiation and to gravitational, electric, and magnetic forces, when-

ever the source is very small as compared to the distance from it. The rapid decrease in intensity of waves from a small source makes it difficult to transmit wave energy over great distances. Of course, where there are reflecting walls and objects, as in a closed room, light or sound intensity does not decrease in so simple a fashion. Then, too, if the medium, say air, is full of smoke or fog which absorbs and scatters light, the light intensity will decrease much more rapidly than in proportion to $1/d^2$. In order to minimize the rapid decrease of wave energy with distance, the energy sometimes is deliberately concentrated by reflectors into a more or less parallel beam, as in a searchlight. Then, of course, the intensity does not decrease as rapidly with distance as it would otherwise.

ENERGY IN SOUND WAVES

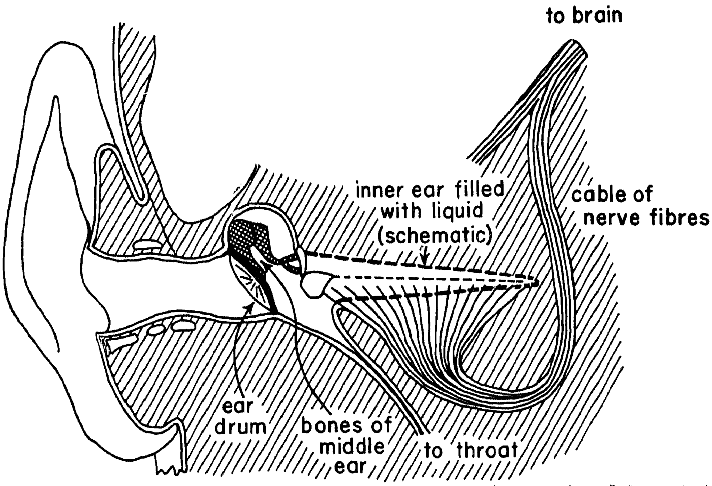
The actual amount of energy in sound waves is very small, for the amplitude of motion of the air molecules is incredibly tiny. Delicate measurements of the pressure changes in sound waves show that in ordinary speech the power output of a person is only about 0.000020 watt. In shouting this may increase to 0.01 watt. For enough power to light even a small electric lamp, 1,000 persons would have to shout simultaneously as loud as they could!

Hearing. The ear is a remarkably sensitive device for detecting sound. Physiologists and psychologists have long been interested in the mechanism of hearing, and the development of the telephone and later the radio and sound films have led physicists to spend a great deal of effort in studying the effects of sound upon the human ear. Dr. Harvey Fletcher and his associates at the Bell Telephone Laboratories are among those who have done outstanding work in this field.

The Ear. Sound waves striking the external ear are led down the small channel (Fig. 171) to a tiny membrane or ear drum which is forced to move back and forth by the pressure variations of the sound waves. These vibrations are transferred from the drum to the small bones of the middle ear, through which they produce compression waves in the fluid of the inner ear. Here the vibrations acting upon sensitive hairs set up nerve impulses for transmission to the brain.

Sensitivity of Ears. Ears differ somewhat in their characteristics, but "normal" ears are sensitive to sound waves ranging in

pitch or frequency from about 20 to about 20,000 vibrations per second. Below 20 vibrations per second, the effect is like a series of pulses rather than a single tone. Fletcher and his coworkers have shown that the actual limiting sensitivity, that is, the minimum



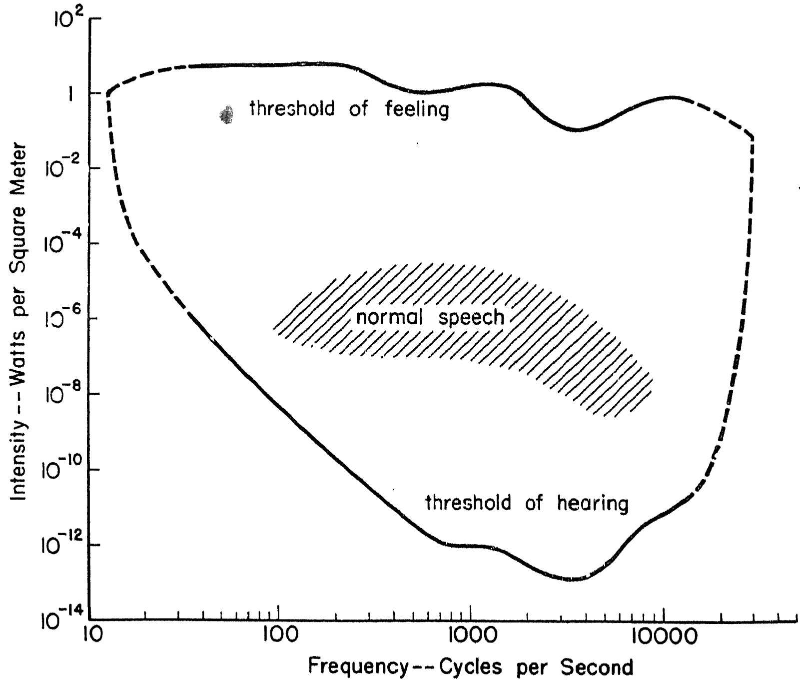
(*After Munson, Bell Telephone Laboratories.*)

Fig. 171. The ear. Vibrations reaching hair cells in the inner ear produce impulses which the acoustic nerve carries to the brain. The inner ear (cochlea), for simplicity shown stretched out, is actually spiraled into a conical form.

"loudness" of sound that can be heard, varies with frequency as represented by the lower curve in the Fig. 172. The ear is most sensitive to sound frequencies of about 2,000 per second. Ears cannot distinguish one sound frequency from another when the intensity is too high, and the sensation becomes pain rather than sound. The upper curve shows the way in which the maximum sound intensity, or the pain threshold varies with the frequency. Any compressional wave which has the proper frequency and intensity to fall inside the area between the upper and lower curves may be heard by the normal ear. Ordinary speech falls in the shaded part of this area.

The ability of the ear to detect changes in pitch or frequency varies considerably with the individual. Many musicians have developed an unusual sense of both absolute pitch and changes of pitch. Some can even sense changes of about 1 per second in a frequency of 1,000 per second.

Loudness and Intensity. Sound intensity is the power per unit area in a sound wave. Intensities to which our ears can respond cover the tremendous range of more than 10^{13} times. Physicists and sound engineers have introduced a special scale of ***loudness.*** It



(*Data from Bell Telephone Laboratories.*)

Fig. 172. Auditory curve. A sound with frequency and intensity value falling within the closed curve is audible to the average human being. Sound with intensity value above the upper curve produces a sensation of pain. Sound with intensity below the lower curve is too faint to be heard.

gives, better than the actual intensities, the relative loudnesses of sounds as they would be judged by the ear. Some idea of the position of various common sounds on this scale is given by Fig. 173. This loudness scale is a "logarithmic" scale, that is, an increase of one step in loudness corresponds to a tenfold increase of intensity. Each loudness step is called a ***bel*** in honor of Alexander Graham Bell, one of the original inventors of the telephone. For convenience the bel is further divided into ten steps called ***decibels.*** The lowest, or zero, level of the scale represents a rate of flow of sound energy corresponding to only 10^{-11} watt/meter^2 of area. A change of 1 decibel in loudness is about the minimum that the human ear can

detect. As this corresponds to a 26 per cent change of intensity, we see that, while accommodating a great range of intensity, the ear actually has poor intensity discrimination.

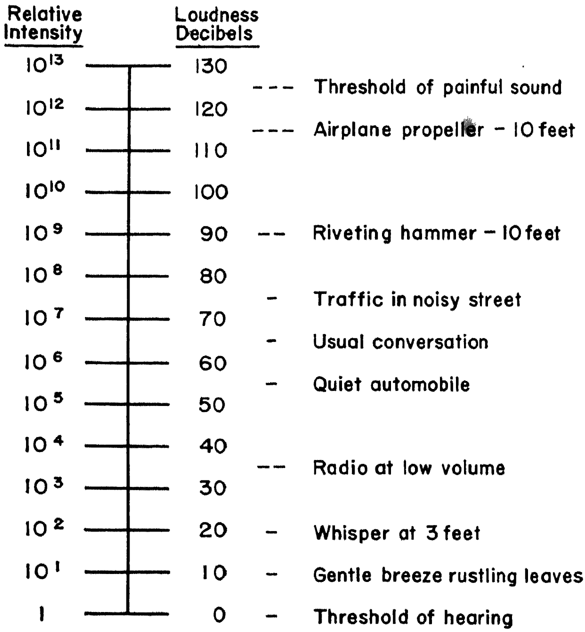
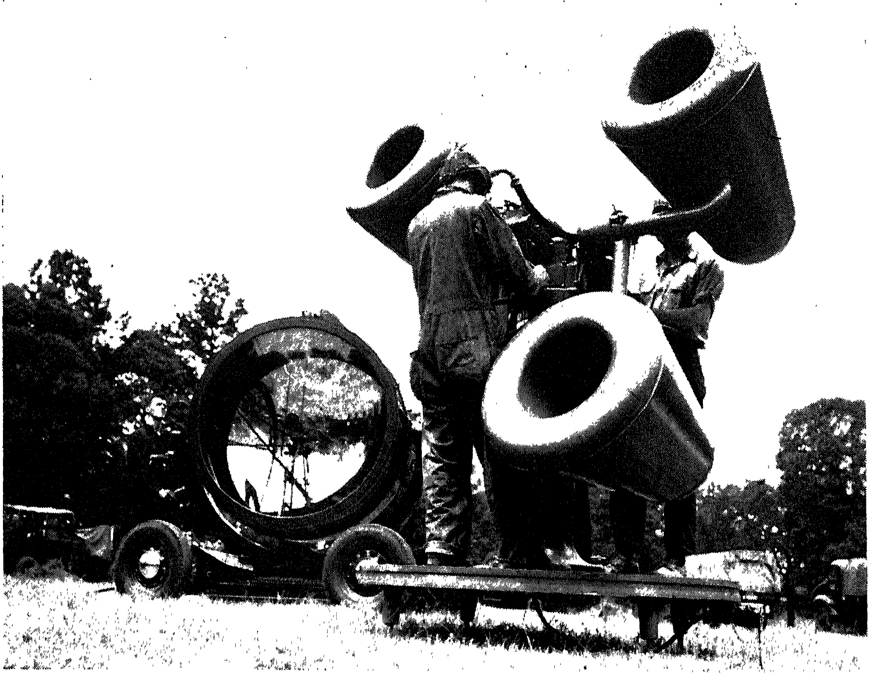


Fig. 173. Decibel and sound-intensity scales.

Noise and Music. When we hear a catgut string being rubbed by some horsehair we may call it music, but when we hear a street car rumbling down the street we call it noise. What actually is the difference?

Perhaps we can find a clue from this experiment: Let us drop a handful of wooden sticks of various sizes on a table—the sound is a meaningless jumble which we call noise. If, however, we drop the sticks one by one, we hear a definite musical sound when each stick falls, the tone or pitch for each stick depending on its form and weight. Noise is ordinarily a mixture of sounds so complex and unrelated, or of such short duration, that it cannot be analyzed by the listener. A musical sound, on the other hand, is either a tone of a single frequency or else a combination of frequencies with some definite relation between them, so that a regular pattern may be recognized by the hearer. Naturally, this distinction is not always very clear-cut. It is not easy to separate psychological reactions to



(*Sperry Gyroscope Company.*)

Fig. 174. Sound locator for airplane detection. The near-by searchlight gives 800 million beams candle power. These detectors are giving way to radio-beam locators (see Chap. XVII).

sounds from the purely physical character of the vibrations. Even many years after the first playing of Wagner's "Tannhäuser Overture" the London *Times* called it "at best a commonplace display of noise and extravagance."

Tools for Studying Sound. Curious men long have wondered about the nature of sounds, but only recently have technical developments made it possible to "see" sound waves so that they may be studied in detail. In the last century some experimenters fastened light straws to paper diaphragms and watched the end of each straw vibrate as its diaphragm was pushed and pulled by the air-pressure variations in the sound waves. A later arrangement was a mirror attached to a diaphragm. A light beam reflected from the mirror would dance when sound waves vibrated the diaphragm, and so trace on a moving photographic tape an outline corresponding to the sound waves (Fig. 175).

The Phonograph. Thomas Edison realized that a needle could be attached to a diaphragm so as to cut on a cylinder wiggly

grooves that followed the pressure variations of incident sound waves. Later he reversed the process by attaching a diaphragm to a needle which was made to follow the same groove. At the first test of his new phonograph he was able to make the vibrating diaphragm repeat, "Mary had a little lamb."

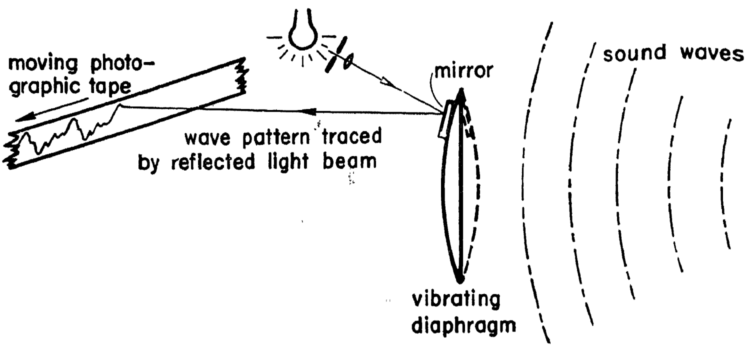


Fig. 175. Simple oscillograph to trace sound-wave patterns.

New Tools. The progressive developments of the telephone, the phonograph, and the radio from early crude forms to their present state have paralleled man's increased knowledge of sound and electricity. Along with these instruments have come excellent devices for showing the nature of sound waves. For example, when the pressure variations of sound waves alternately push and pull the diaphragm of a microphone, the mechanical vibrations produce electrical pulsations. The latter, when amplified, can cause an electron beam to trace on the screen of a cathode-ray oscilloscope, an outline representing the original sound wave. For the present let us think of such devices simply as tools with which to study sound. Later, we shall learn more about their electrical operation.

Quality of Sound. When a tuning fork is struck near a microphone the sound trace on an oscilloscope shows, as we might expect, that a single "pure" tone is produced by the simple harmonic motion of the prongs. When stiffer, shorter forks are struck, more vibrations per second occur and hence more wave crests appear on the screen —twice as many if the frequency is twice as great, three times as many if the frequency is three times as great. The amplitude of each trace is proportional to the maximum variation of sound pressure from normal.

(*Bell Telephone Laboratories.*)

Fig. 176. Portion of a phonograph record (magnified 33 diam.). In the common lateral-cut record the reproducing needle is moved from side to side by the wavy groove, the form of which corresponds to the recorded sound wave. This motion of the needle may be directly converted into a sound wave similar to the original by causing a diaphragm to vibrate. In the newer phonograph "pickups" these vibrations of the needle are first converted into electrical pulsations which are amplified and then converted into sound waves by a loud speaker.

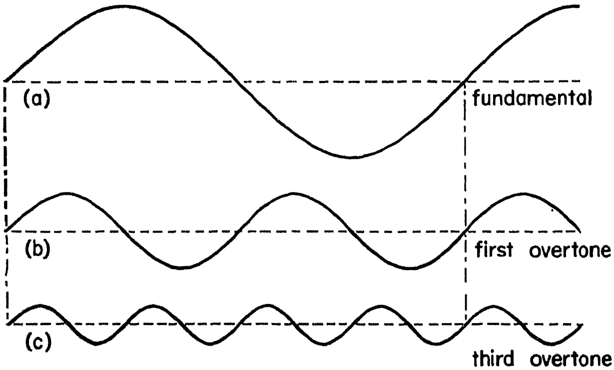


Fig. 177. Oscillograph patterns of a fundamental frequency (a) and its first (b) and third (c) overtones.

You will probably recall from your trigonometry that curves such as in Fig. 177 (where damping is negligible) are typical graphs of *sines* (or *cosines*), and each complete vibration corresponds to the variation of the sine of an angle which changes from 0 to 360

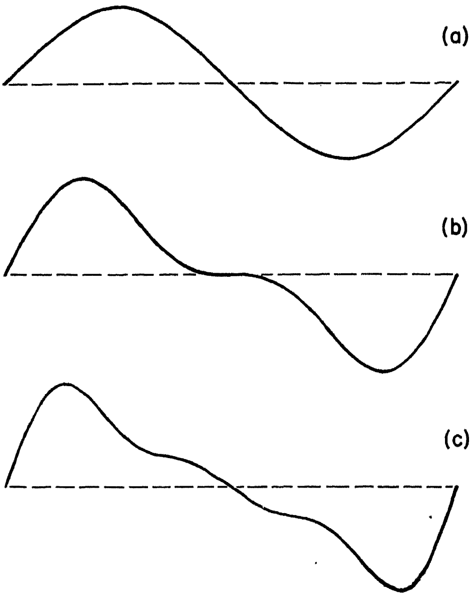


Fig. 178. Oscillograph records of sound from a string vibrating (a) at its fundamental frequency; (b) its fundamental frequency plus first overtone; and (c) its fundamental frequency plus first and second overtones.

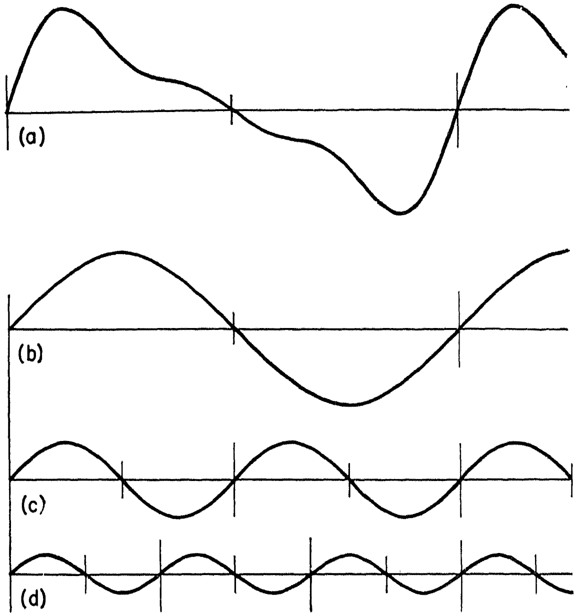
deg. One can describe very simply the "pure" sound waves represented by these traces by saying that the variation of pressure from its average value at any time t is given by

$$\text{Pressure variation} = A \sin 2\pi ft$$

where A is the amplitude (maximum variation) and f is the frequency.

What makes a violin sound different from a piano, a clarinet, or a saxophone giving the same note? Most sounds are not simple, for the sound sources usually vibrate in a complicated fashion. A string, for example, can be made to vibrate in the simple fashion shown in *a* (Fig. 178) if plucked exactly halfway between the

center and an end. In that case a single pure tone, called the *fundamental,* is heard directly and "seen" indirectly on an oscilloscope. The string can also be made to vibrate in a more complex mode as in *b*. Here the same fundamental tone is heard, but there is



ig. 179. Oscillograph patterns (a) of a complex vibration, and of its components: (b) the fundamental and (c) first and (d) second overtones.

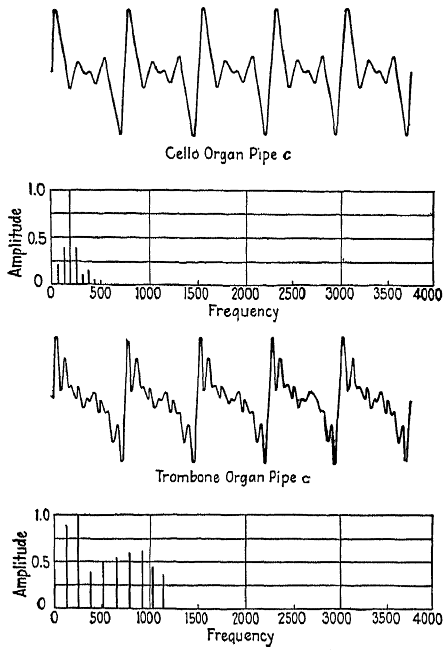
in addition a tone of *twice* the frequency of the fundamental. This new tone is usually called the first *overtone.* The string can likewise be made to vibrate as in *c*. The sound that is heard in this event is the superposition of the fundamental, first, and second overtones.

These pure tones combine, in the manner shown in Fig. 179 to form the resultant complex wave trace at the top. The trace of this complex wave is what we would see on an oscilloscope screen. The quality of a musical sound, then, depends on the frequencies and relative amplitudes of the pure tones that combine to produce the final complex sound.

The strings of most string instruments are deliberately struck or bowed near the end in order to accentuate the overtones. The sounding boards of the various instruments still further emphasize the differences in overtones. A piano string may produce as many as

ten to twenty overtones. Wind instruments likewise have overtones which depend in number and intensity on the construction of the tone chambers and operation of the instruments.

"Sound spectroscopes" have been developed which analyze a complex wave and measure the relative intensities of its various component frequencies. Some typical sound spectra are shown in Fig. 180.



(*D. C. Miller.*)

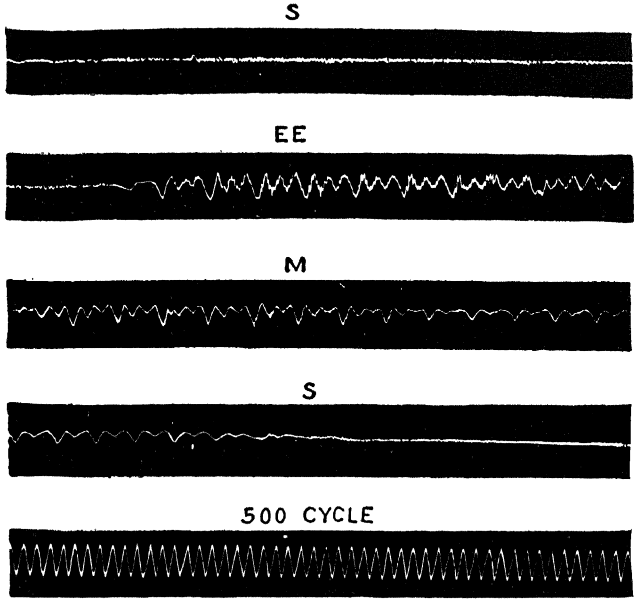
Fig. 180. Wave forms and frequency analyses of musical sounds. Two instruments sounding the same note give quite different wave forms because they have overtones of differing intensities.

With such great differences in the number and intensities of overtones, no wonder a piano sounds different from a clarinet. Human beings, with all their possibilities for different throat, mouth, and nasal formations as well as differences in the vocal cords and their mode of use, naturally show tremendous variations in the quality of vocal sounds. What makes a Caruso or Tibbett different from the rest of us?

Although there remain many interesting things about sound, the scope of this book hardly permits going further with them. If curiosity has been stimulated, Professor D. C. Miller's book *The Science of Musical Sounds*, or Dr. Fletcher's *Speech and Hearing* will be found most interesting.

Acoustics. The possibility of controlling the flow of sound energy in rooms and auditoriums is of great value to office and shop workers as well as concert, lecture, and theater audiences. The prevention of undesired reverberation, bad echoes and "dead spots," while at the same time allowing enough reverberation to assure "brilliance" of musical sounds, is becoming less a matter of chance and more a science. New sound-absorbing materials for "acoustic correction," combined with the opportunity for sound

reinforcement by microphones, amplifiers, and loud-speakers, give added scope to the ingenuity of engineers and architects interested in designing new buildings or correcting acoustical faults in old ones.



(*D. C. Miller.*)

Fig. 181. Wave forms of the parts of the word "seems" pitched at 500 cycles.

FOR STUDY AND READING

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SUMMARY

Wave motion transports energy and may be identified by ***interference***. Standing waves result from the interference of a reflected part of a series of waves with an unreflected part.

If wave disturbances are in the direction of propagation, the wave is ***longitudinal.*** If they are perpendicular, the wave is ***transverse.*** Sound is a longitudinal pressure wave and may travel in any medium. The velocity of sound in air is about 1,100 ft/sec (330 meters/sec), and it is greater in liquids and solids.

The most common form of free vibration is ***damped simple harmonic motion,*** that is, with decreasing ***amplitude.*** Its ***frequency*** is the inverse of its ***period.*** Every vibrating object has at least one ***characteristic*** frequency which depends on the mass and the elastic properties. Energy pulses produce ***resonance,*** or a relatively large vibration of an elastic object, only when they have a frequency near a characteristic frequency of the object.

A vibrating object produces in air next to it pressure changes that travel outward as sound waves. The speed of any wave is the product of its ***wave length*** and its frequency. The ***intensity*** of a wave from a very small source is inversely proportional to the square of the distance from the source, if none of the energy is absorbed or reflected.

The normal human ear can detect sound intensities less than 10^{-11} watts/meter^2 and up to 100 watts/meter^2 without pain. Frequencies below about 20,000 cycles/sec are detectable, but below 20 cycles/sec the sound is like pulses rather than a musical tone. ***Loudness*** as judged by the ear is related to a scale on which an increase of one unit (called the ***bel***) corresponds to a tenfold increase of intensity. The ***decibel,*** one-tenth of a bel, is the unit of loudness used by sound engineers.

Noises and musical sounds differ in complexity and regularity. The "forms" of sound waves may be analyzed by ***oscilloscopes.*** A simple harmonic vibration produces a "pure" tone, of which the oscilloscope trace is a sine curve. Most musical sounds are not pure tones, but each consists of a ***fundamental*** tone to which are added various ***overtones.*** The ***quality*** of a musical sound depends upon the number and intensities of the overtones.

Acoustics is concerned with the proper distribution of desired sound energy and the suppression of unwanted sounds in rooms, auditoriums, etc.

QUESTIONS

1. What characteristics do the various types of waves, such as ***water waves, sound waves,*** and ***light waves,*** have in common?
2. Do all waves require a physical medium for the transmission of energy?

3. Knowing sound energy to be the transmission of mechanical energy impulses from molecule to molecule, why should one expect sound to travel more slowly (1,100 ft/sec, 330 meters/sec) than light (186,000 miles/sec or 3×10^{10} cm/sec)?
4. Why do we believe sound waves to be ***longitudinal*** and light waves ***transverse?***
5. In what ways are the following terms used to describe wave motion: frequency, period, amplitude, wave length?
6. The spring of Fig. 103, page 154, was found to have an elastic constant of -3.7 newtons/meter. What would be its characteristic frequency if a mass of 0.1 kg were attached to its end?
7. The fundamental relation governing all wave motion is

$$\text{Velocity of propagation} = \text{frequency} \times \text{wave length}$$

What is the wave length of the radio wave from WABC if the frequency is 880 kilocycles/sec?
8. What effects of resonance have you observed?
9. Under what conditions do we find that the ***intensity*** of wave energy (the energy per second falling on a unit of normal surface) is inversely proportional to the square of the distance from the source ($I \propto 1/d^2$)?
10. If a glowing tungsten filament can just be seen at a distance of one mile under the most favorable conditions, how far away would you expect to be able to see it if the luminous power output were doubled?
11. If you should move from the first row at a symphony concert, 15 ft from the center of the orchestra, to the balcony, 150 ft away, would you expect the sound intensity to decrease by a factor of 100? What if the concert were out of doors?
12. Are the ears and eyes good instruments with which to measure sound and light energy? Are they more in error in estimating intensity or in estimating frequency?
13. What devices transfer wave energy to other forms? The reverse? Consider the chain of energy conversions involved in the detection of the light energy from a projection lamp by a thermopile, amplifier, and galvanometer.
14. Why does middle C on a piano sound different from the same note from a tenor saxophone?
15. Of what importance is the study of acoustics?

CHAPTER IX

ELECTRIC ENERGY

Until little more than one hundred years ago, the most familiar effects of electricity were the tremendous zig-zag flashes of lightning across the heavens and the reverberating crashes of thunder that followed. Before 1752, when Benjamin Franklin flew

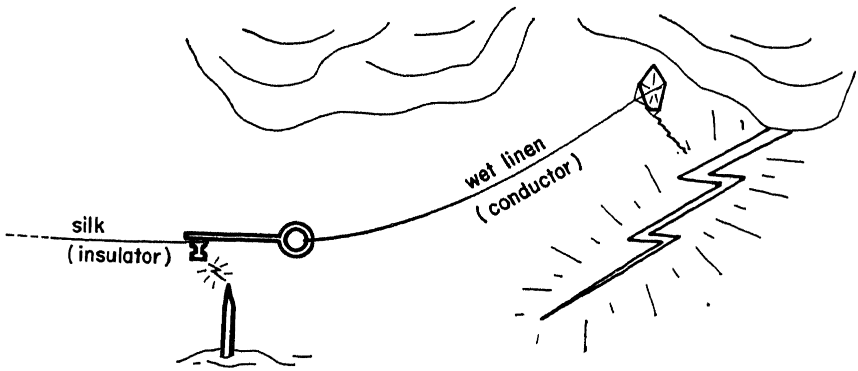


Fig. 182. Franklin demonstrated that lightning is electricity.

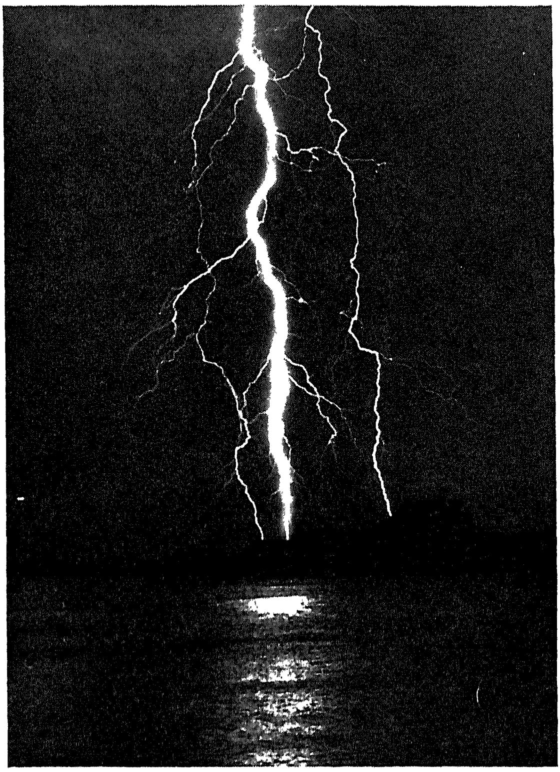
his kite during a thunderstorm and drew sparks from the wet string, it was hardly suspected that lightning was related to other known electrical phenomena such as the sparking of cats' fur.

In a comparatively short time electric energy has been tamed and put to work. Its importance is attested by the number of times daily that each of us throws an electric switch and by the regularity with which electricity is involved in our economic and political considerations. The ease with which electricity can be transmitted to the place most needed and converted into other forms of energy makes it generally the most convenient form in which to utilize energy. It can be put to work to run machines, to produce heat and light, to carry sound and pictures, and, in fact, to do almost any reasonable task. Moreover, its new uses seem to keep pace with our understanding and ingenuity. Why has electric energy such unusual

adaptability? Perhaps we can begin to see the answer when we learn more about electricity and its close connection with matter itself.

ELECTROSTATIC PHENOMENA

Early Experiments. William Gilbert (1540–1603), Stephen Gray (1670–1736), Luigi Galvani (1737–1798), and other early experimenters with electricity amused themselves and the public by electrifying all kinds of materials by friction and making frog legs "kick" when stimulated by electric sparks. About the nature of electricity, however, they contributed little more than a great deal of speculation.



(Brown Photos.)

Fig. 183. Lightning stroke on the Isle of Jersey.

Gradually more definitive experiments were performed. Glass could be "electrified" by rubbing with silk, but when substances

like hard rubber or sealing wax were electrified by rubbing with fur the electricity behaved in a different fashion. Two electrified pith balls repelled each other when both had been touched with the same "charged" glass or hard rubber. However, when one pith ball was "charged" by glass and the other "charged" by hard rubber, the two balls attracted each other. This was taken to indicate two types of electrification, and it was agreed arbitrarily to say that the glass "accumulated" *positive* electricity when rubbed by silk, while the hard rubber "accumulated" *negative* electricity when rubbed by fur.

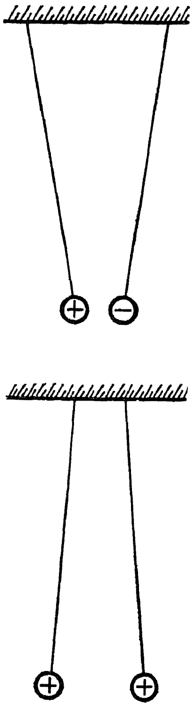


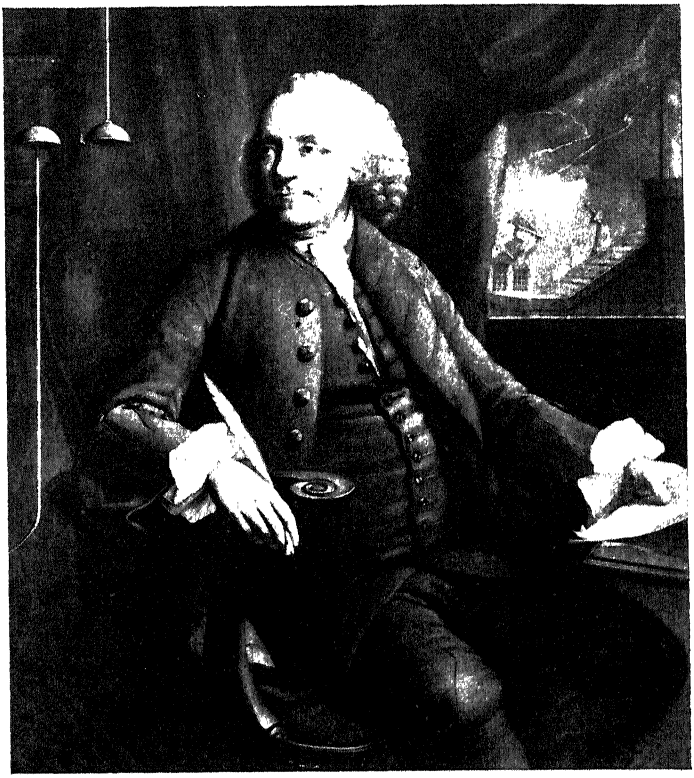
Fig. 184. Charged pith balls suspended on silk threads; "like charges repel—unlike charges attract."

The Nature of Electricity. For our purposes it is not necessary to go through the history of the philosophical and experimental arguments about the cause and nature of electrification. Some believed that electricity was a "fluid," others thought that it must be two fluids, one positive and one negative.

In the thick of this controversy was Benjamin Franklin (1706–1790). In addition to his diplomatic and social accomplishments, Franklin was an exceptionally ingenious experimenter. The role he played in clarifying physical ideas and stimulating scientific work, both in this country and in England, is only beginning to be appreciated.

According to our present view, ordinary matter is electrical in nature and is made up of two kinds of electricity. Every atom contains a definite number of tiny units of positive and negative electricity, and normally the number of negative units exactly equals the number of positive units. Thus, because the effects of the two kinds of electricity neutralize each other, all matter is normally *neutral* or effectively uncharged. The elementary unit of negative charge we now call the *electron*. The elementary unit of positive charge commonly appears on the *proton*. These two units of electric charge are equal in magnitude but opposite in "sign." When two substances are rubbed together, some of the negative electrons can be "scraped" off the surface of one and added to the surface of the other. When silk rubs glass, negative electrons are scraped off the glass and onto the silk, so the silk becomes

"charged" negatively. The glass is left with less than its normal quota of negative electrons; in other words, it becomes positive. When fur rubs hard rubber, negative electrons are scraped off the fur onto the hard rubber, so the hard rubber becomes negative and the fur positive.



(Metropolitan Museum of Art.)

Fig. 185. Benjamin Franklin, by E. Fisher after Chamberlin.

Electrical Forces. We have learned of Newton's great conclusion that the gravitational force of attraction between two bodies is proportional to the product of the masses and inversely proportional to the square of the distance between them (pages 59, 148):

$$F = G\frac{m_1 m_2}{d^2}$$

Almost at the same time that Cavendish in England showed experimentally the correctness of this idea of Newton's, a French physicist named Coulomb performed a similar experiment for electrical

forces. A light crossarm AB with metal ends (Fig. 186) was mounted on a very thin fiber F. An electric charge Q_1 placed on ball A, and a second charge Q_2 placed near Q_1, produced mutually attractive electrical forces if the charges were of opposite sign. The force on A

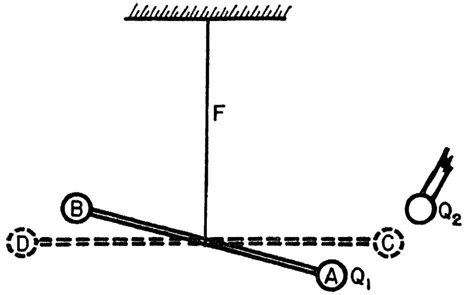


Fig. 186. Coulomb measured forces exerted by charged objects on one another.

caused the crossarm to rotate, twisting the fiber, to the new position CD. Coulomb measured the force exerted by the twisted fiber for numerous values of Q_1, Q_2, and of the separation. He concluded that the electrical force on either charge was proportional to the product of the charges, and inversely proportional to the square of the distance between the charges, or

$$F = K\frac{Q_1Q_2}{d^2}$$

Here d is the distance between the charges Q_1 and Q_2. We often use as the unit of electric charge the ***coulomb,*** which is defined so that, if d is in meters and the force is in newtons, the constant of proportionality in the last relation (if there is no matter between Q_1 and Q_2) is

$$K = 9 \times 10^9 \frac{\text{newton-meter}^2}{\text{coulomb}^2}$$

The forces are attractive for unlike charges, repulsive for like charges. The similarity of Coulomb's law for electrical forces to Newton's law for gravitational forces is very striking. Could it point to some connection between them? Actually, this is still an open question.

The basic unit of electric charge is the charge of the electron. The measurement of this tiny quantity has provided the subject for

a fascinating story of modern physics. For our present purposes it is enough to say that the charge on a single electron is exceedingly small, only about 10^{-19} coulomb of negative electricity!

Electroscopes. One of the simplest ways of measuring electric charge

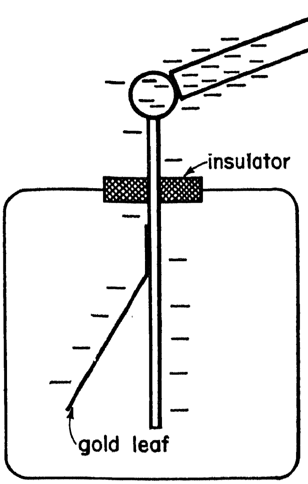


Fig. 187. Electroscope charged by contact.

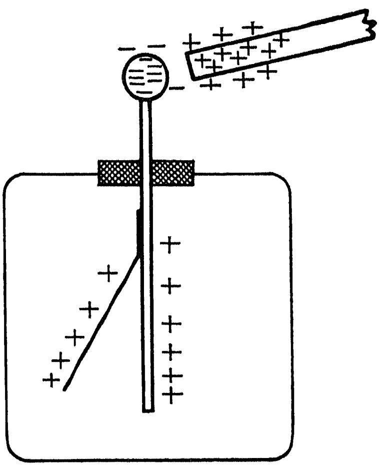


Fig. 188. Electroscope charged by induction.

makes use of the mutual repulsion of like charges. In the typical electroscope a thin foil of light gold leaf is mounted on an insulated vertical metal support. When the support is touched with an electrified hard rubber rod, both the leaf and its support are charged negatively. These like charges repel each other, causing the leaf to bend away from the rod by an amount that depends on the magnitude of electric charge and the stiffness and weight of the leaf. These instruments are made in many forms, and some are so sensitive that they can measure the effect of only a few hundred electrons.

Induced Electricity. With the aid of an electroscope an effect may easily be detected which at first sight seems strange. It is the ability of an electrically charged body to *induce* another electric charge in near-by bodies. If a positively charged glass rod is brought *near* an electroscope, the leaf bends away from its support. A charge has been induced on the electroscope by "action at a distance" even though the charged glass rod does not touch the electroscope! Investigation shows that part of the electroscope near

the positive glass rod has an opposite (negative) charge induced in it, while the parts farthest away have a positive charge. When the charged rod is removed, the charge of the electroscope returns to zero. The induced charge is explained simply as the effect of the attraction between a positive charge, say, and the electrons in the initially uncharged body. The electrons are displaced a bit toward the inducing positive charge, making a negative charge on that end of the body and leaving an equal positive charge on the opposite end.

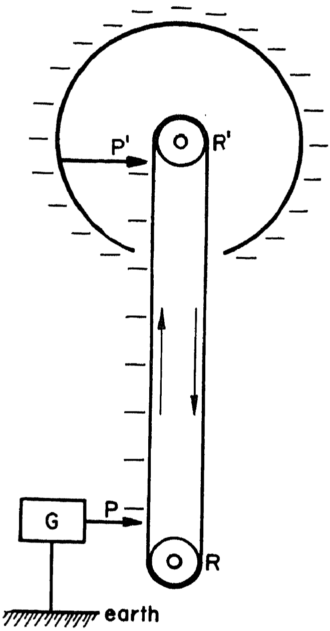
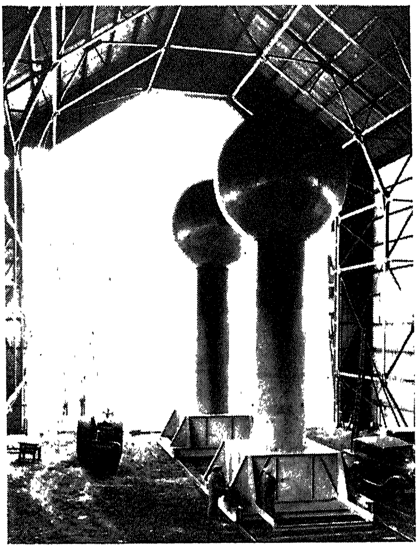
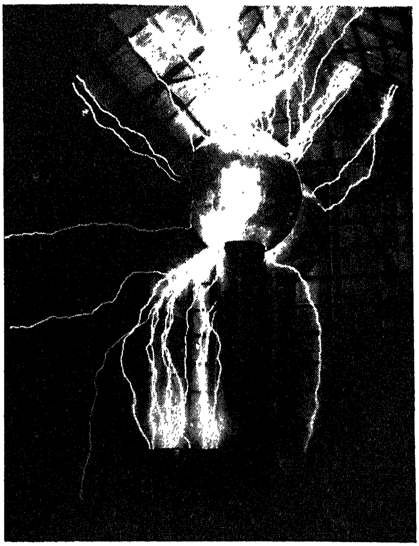


Fig. 189. Principle of Van de Graaff electrostatic generator.

Conductors and Insulators. In our brief survey of some important properties of matter in Chap. IV, we learned something about the differences in the way in which materials *conduct* electricity (see page 171). In materials that can be electrified, such as glass, amber, and hard rubber, the electric charges do not move very much. These substances are ***insulators***. On the other hand, electric charges placed on materials like metals move about very easily. Such substances are good conductors. Actually we learned that there is no sharp distinction between conductors and insulators, but simply that substances may differ enormously in conductivity.

Moving Electric Charges. When electric charges are added to or taken from insulators, or when electric charges move through conductors, experiments show that in general it is the negative electrons that actually move. As we learn more about electrons this will seem quite reasonable, because an electron weighs only about 1/1,800 as much as the positive part of a hydrogen atom, or proton, which is the lightest of the ordinarily available carriers of positive electricity. Therefore, electrons are much more easily moved than the heavier positive cores of atoms. In some circumstances, however, the positively charged particles can be made to move appreciably. An electric current in a metal conductor, then,





(R. J. Van de Graaff.)

(a) (b)

Fig. 190. (a) The first large Van de Graaff electrostatic generator at Round Hill, Massachusetts. (b) Two and a half million volt spark discharge from one sphere of generator to the surroundings.

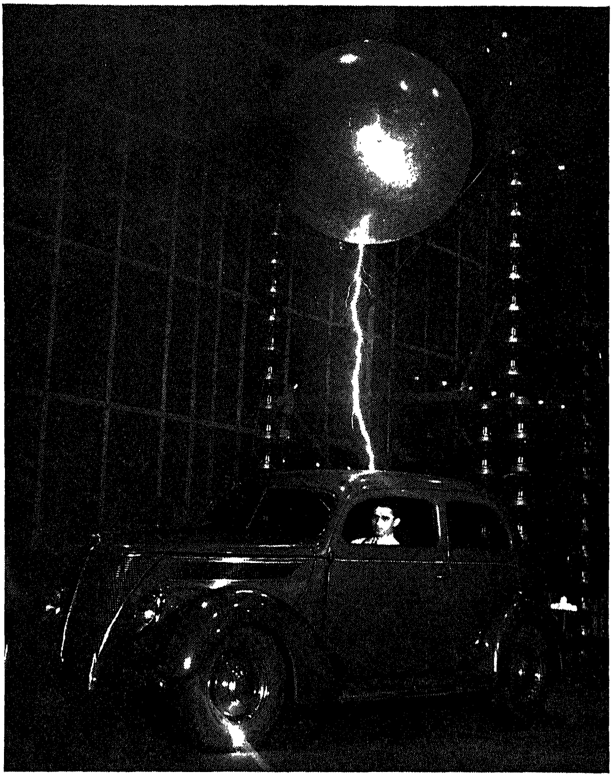
is nothing more than the flow of negative electric charges (electrons) along the conductor.[1]

Electrostatic Generators. Various friction electrical machines, sometimes called "static" machines, were built years ago to accumulate quite large electric charges. They have not found wide practical use, partly because it is not easy to build up large quantities of electricity. On all but the driest days difficulty is experienced from the tendency of charges to "leak" off even the best insulators.

The Van de Graaff Generator. In recent years an improved electrostatic generator was developed by Van de Graaff (Fig. 189). A large copper sphere is mounted on an insulator (not shown). An endless belt of some insulating material, silk or rubber, runs up from the lower roller R over the upper roller R' and back again.

[1] Carried down to us from the time when little was known about the nature of electric current is the custom of referring to the direction of current as ***opposite*** to what we now know to be the direction of electron flow. In other words, if a negatively charged object and positively charged object are connected by a conductor, the electron flow, or the ***electron current,*** is from negative to positive, but according to older usage the ***current*** is directed from positive toward negative.

This belt is made to move at high speed by a motor attached to the lower roller. Electrons then are sprayed onto the belt from some points at P when the points are charged by means of an electrical generating device G. These electrons are carried by the belt up into



(Westinghouse Electric and Manufacturing Company.)

Fig. 191. Three million volt spark strikes car without harming occupant. Faraday showed that electric charge placed on a hollow conductor stays only on the outside surface. (The charges repel each other and so are forced to the outer regions of the conductor.) The metallic body of the car is thus an almost perfect electrical "shield" for the man within.

the sphere where they are removed by the point P' and so are transferred to the sphere.

This process of accumulating electric charge continues until finally another factor comes into play. Air is not a perfect insulator, and when the sphere is charged more and more the surrounding air eventually "breaks down" and becomes conducting. The electricity leaks off to the surroundings, either gradually or as a sudden

large spark. Electricity escapes easily from points and much less readily from large, smooth, spherical surfaces. If the sphere of an electrostatic generator of this type is made very large, say three meters in diameter, it may be charged to a ***potential*** of several million volts![1] When the potential becomes so great that the breakdown point for the air is reached, giant sparks which rival lightning jump from the sphere to near-by "grounded" objects. These great potentials are useful for "atom-smashing" experiments, and for the production of high-voltage X rays, both of which we shall discuss later. However, the electric current represented by the electric charges moving with the belt up to the sphere is very small indeed, so at present it does not seem likely that such electrostatic generators will prove useful for the large-scale "production" of electric energy.

THREE IMPORTANT CONCEPTS—POTENTIAL, CURRENT, RESISTANCE

Making Electric Charges Move. All matter normally consists of equal numbers of elementary positive and negative charges which are usually tied more or less tightly to their own atoms. In order to produce an ***electric current,*** it is necessary to make these charges move, and this requires that a force be exerted on them. We say that there is a ***difference of potential*** between the two ends of a wire when there are forces that make the charges in the wire move as an electric current.

Difference in Potential. Let us see what is the meaning of this "difference of potential" which accompanys electrical forces. If a charged particle is made to move against an electrical force, work must be done on the charge, and accordingly, potential energy must be added to it. When the particle is made to move from one point to another, the number of joules of potential energy added to the particle per coulomb of charge on it is called the ***potential difference*** between the two points. The usual unit of potential difference is the ***volt.***

When there is an electrical force which could move a free positive charge from one point to another, the first point is said to be

[1] As described later on this page, the potential of the sphere (or, more properly, the potential difference between the sphere and the earth) is a quantity which tells how much electric potential energy is gained by the sphere when charge is carried to it. The potential is directly proportional to the quantity of charge on the sphere. The unit of potential is the volt (or the joule per coulomb).

at a ***higher*** potential than the other, or it is said to be ***positive*** with respect to the other.

The name "volt" was chosen for the unit of potential difference in honor of Alessandro Volta (1745–1827), who was one of the first to find that potential differences could be produced by chemical effects or that chemical energy could be converted into electric energy. Before then only friction was known to produce electrical forces. Nearly every day most of us use Volta's ideas in some modern development such as dry cells in flashlights or storage batteries in automobiles.

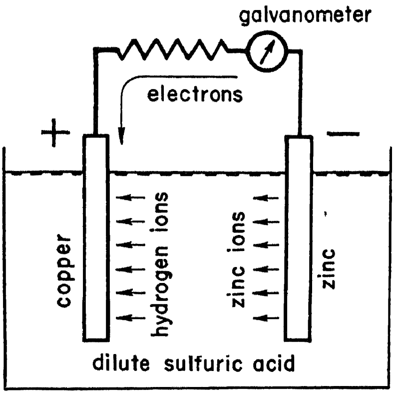


Fig. 192. Type of Voltaic cell.

Electric Cells. Volta found that potential differences exist between dissimilar metals such as copper and zinc when they are placed in acid, alkaline, or salt solutions. Such a combination is called an electric cell, and the metal pieces are called electrodes. In the dry cells of today, a central carbon rod usually serves as the positive electrode and an outer zinc container as the negative electrode. A mixture of chemicals such as ammonium chloride and manganese dioxide fills the space between the positive and negative electrodes.

When there is no current in a cell, the potential difference between the terminals is called the ***electromotive force*** (EMF). For a common dry cell this electromotive force is about 1.5 volts. Increasing the size of a dry cell does not change its characteristic potential difference, which is determined only by the active materials. But it does increase the amount of chemical energy contained, and, accordingly, the amount of electric energy that the cell can produce before it is exhausted.

The action of a cell of the type illustrated in Fig. 192 is approximately as follows: zinc tends to go into solution as positively charged zinc atoms, or ions. Each positive zinc ion that goes into the solution leaves a corresponding excess ***negative*** charge on the zinc electrode. At the copper electrode, positive hydrogen ions from the dilute sulfuric acid (H_2SO_4) take electrons from the copper to form neutral hydrogen atoms. This leaves the copper electrode

with a deficiency of electrons, or, in other words, an excess ***positive*** charge.

In setting up the excess of negative charge on the zinc electrode and the excess of positive charge on the copper electrode, chemical energy is transformed to electric energy. Thus there is established a potential difference between the two electrodes. There will be no electric current until an external conducting wire is connected between the two electrodes. Then, negative electrons flow through the conductor to the positive electrode.

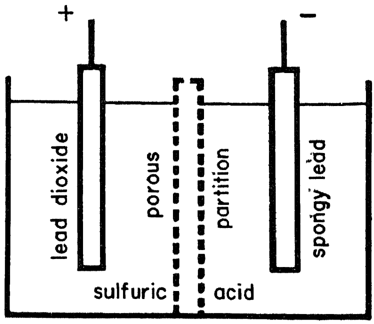


Fig. 193. Lead storage cell.

Lead Storage Cells. The lead storage cell, in contrast to the dry cell or the cell just described, is a ***conveniently reversible*** cell. The negative electrode is usually a plate of spongy lead, and the positive electrode a plate of lead dioxide (PbO_2). The plates are placed in a sulfuric acid solution and develop an electromotive force of 2 volts per cell. During use, or discharge, chemical energy is converted into electric energy, and both plates are changed gradually to lead sulfate ($PbSO_4$). After use, by setting up a current through the cell in the reverse direction, the chemical reaction can be reversed and the cell brought back to its original condition. In other words, the cell is ***charged*** by changing electric energy into its chemical form; so, in effect, electric energy is "stored" for future use. Your automobile has a small generator which normally charges the battery when the motor is running. When the battery is called on to operate lights, ignition system, radio, a heater fan, and a horn, it has quite a task to perform. Unfortunately lead cells are very heavy and bulky for the amount of energy stored, and although much effort has been spent to make cells capable of storing more energy per pound of weight, there has so far been no great success.

Standard Cells. The Weston normal cell, which contains mercury and cadmium as electrodes, has such a constant electromotive force that it is used widely as a standard. The Weston cell has an electromotive force of 1.0183 volts at 20°C, but it is meant to supply only very small currents. Cells of this class are used almost exclusively for comparison in the measurement of potential differences.

Cells in Series—Batteries. When cells are connected as in Fig. 194 (that is, in ***series***), they are commonly called a ***battery.*** The voltage of a battery of cells is the sum of the individual voltages. The standard automobile battery consists of three cells of two volts each, with a total of six volts.

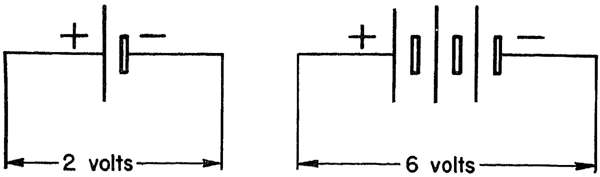


Fig. 194. The voltage of a battery of cells in series is the sum of the individual voltages.

Occasionally two or more similar cells are connected in ***parallel,*** *i.e.*, terminals of the same polarity are connected together. The voltage developed is the same as that of a single cell, but correspondingly larger currents may be drawn.

Electric Currents in Wires. When the two ends of a conductor are connected to two points at different potentials, such as the terminals of a battery, we say that there is an electric current in the conductor. What actually happens?

The conductor had equal numbers of positive and negative charges in its atoms, and we want to know how these charges can be made to produce a current. Recent work shows that in metals the atoms are packed so closely that they overlap to some extent, so that it is comparatively easy for the outer electrons to pass from one atom to another if a small force is applied to them. The battery causes a potential difference between the ends of the wire, and thus provides forces that make the negative electrons in the wire move toward the point of higher potential. This electron flow toward the positive electrode is the electric current. Naturally, materials differ considerably in the ease with which electrons can be made to migrate from atom to atom.

The magnitude of the current depends simply on the ***rate of flow of electrons along the conductor.*** That is, if each electron carries an electric charge which we may call e, the ***electric current*** is determined by the net number of electrons per second carried through a section of the wire. If n electrons move through the section each second, the charge moved per second will be ne.

The usual unit of current, the *ampere,* is one coulomb of charge per second crossing a section of the wire. The ampere was named in honor of André Ampère, the French physicist who did much of the early work on electric currents. Actually the electron is so small a charge that 10^{19} of them must pass through each section

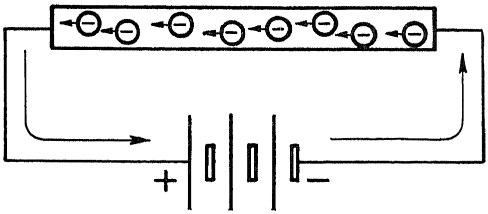


Fig. 195. Current in a metallic conductor is a flow of electrons (schematic diagram).

of a conductor per second for a current of one ampere. Of course, it follows that, if the current is steady, the total charge passing through the section in a certain time is just the product of the current and the time.

It is important to understand that steady electric currents ordinarily exist only in *complete circuits,* for such currents are simply the continuous circulation of electric charges. The source of voltage circulates electric charges around through conductors and back again, much as a centrifugal pump circulates water. Furthermore, a steady electric current, like a water current, has the same value at all parts of a simple unbranched circuit.

Resistance. When a potential difference is maintained between the two ends of a conductor, the electric current would be limited only by the number of electrons available (which is almost countless) if it were not for the effect of electric resistance. This effect comes about because the moving electrons do not pass freely through the conductor, but bounce off atoms of the conductor or trade places with electrons in them. The increased agitation of the atoms means an increase in heat energy. The greater the electric current, the more electric energy is changed to heat energy, and the electric current cannot exceed the value at which all electric energy becomes heat energy.

What would be the effect of increasing the resistance of a conductor? We can say immediately that the potential difference (between the ends of the conductor) needed to produce a given

current would increase. To agree with this qualitative idea and yet form an accurate concept, the ratio of the potential difference to the current produced is called the electric ***resistance.*** In mathematical form

$$\text{Resistance} = \frac{\text{potential difference}}{\text{current}}$$

The resistance unit is the ***ohm*** if the potential difference is in volts and the current is in amperes.

The resistance of a wire is inversely proportional to the electric conductivity of its material, and, as we have learned, materials differ tremendously in conductivity. Obviously, the resistance of a conductor depends on its size and shape as well as the nature of the material. The larger the cross-sectional area of the conductor, the smaller the resistance. The longer the conductor, the greater the resistance. In fact, the resistance of a uniform conductor is directly proportional to the length and inversely proportional to the area. We can put these ideas in the more compact form

$$\text{Resistance} = R_s \frac{\text{length}}{\text{area}}$$

Here R_s is a factor, called the ***resistivity,*** characteristic of the material itself. Resistivity is simply the inverse of conductivity.

Ohm's Law. Early experiments with electricity were difficult to perform in a quantitative fashion, because instruments to measure electrical effects were crude. Indeed, even hazy ideas on electrical phenomena were long in developing. George Ohm (1789–1854) in Germany made some of the first good experiments on relations between the three important quantities, ***potential difference, current,*** and ***resistance,*** and so clarified the picture of electrical effects.

If we use some modern instruments, ***voltmeters*** to measure potential differences and ***ammeters*** to measure currents, the situation discovered by Ohm can easily be understood. The wavy line in Fig. 196 is the schematic representation of a wire that has resistance. This wire is connected to a battery by heavy copper wires with negligibly small resistance. It is so arranged that one, two, three, or up to six cells of the battery may be used in series. An ammeter to measure the current in amperes in the circuit is

placed ***in series*** with the cells to be used and the wire under test, and a voltmeter is placed ***across*** the wire under test to measure the potential difference in volts between its ends which is effective in driving electrons toward the positive end. Suppose that we take the readings of the voltmeter and ammeter with various numbers of cells connected to the wire. Typical results are plotted in Fig. 197.

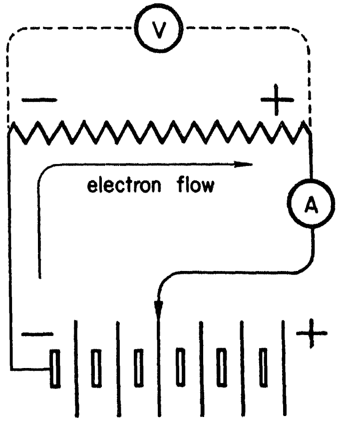


Fig. 196. Circuit for determining the relation between current in a resistance and voltage across the resistance.

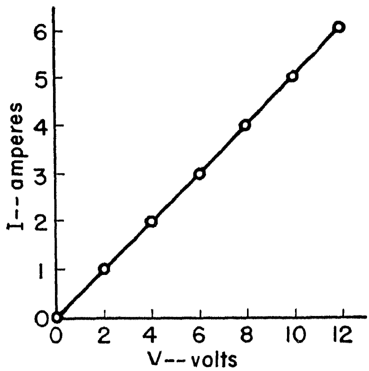
The current I that is in the wire is directly proportional to the applied voltage V, and when one is plotted against the other the result is a straight line. Another statement of Ohm's law, as this relation is called, is that the resistance R is constant

$$R = \frac{V}{I} = \text{a constant}$$

Often it is convenient to express this relation as

$$V = IR \qquad \text{or} \qquad I = \frac{V}{R}, \text{ where } R \text{ is constant.}$$

Ohm's law holds strictly only for metallic conductors, and for



Voltage (V)	Current (I), Amp
2.0	1.0
4.0	2.0
6.0	3.0
8.0	4.0
10.0	5.0
12.0	6.0

Fig. 197. The current in a metallic resistance is proportional to the voltage across the resistance if the temperature does not change.

them only if the temperature does not change. It is exceedingly fortunate that this electrical relation is a simple proportionality much like Hooke's law, for it simplifies calculations concerning

many electrical phenomena. If an unkindness of nature had made this relationship a complicated one, all of our electrical development would surely have been delayed!

FOR STUDY AND READING

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SUMMARY

Two kinds of electricity, ***negative*** (electrons) and ***positive*** (on protons), are present equally in normal atoms. Unlike charges attract each other, and like charges repel, with forces which are

$$\text{Force} = \text{constant} \frac{(\text{first charge})(\text{second charge})}{(\text{distance between charges})^2}$$

The charges will be in ***coulombs*** when the above constant is

$$9 \times 10^9 \text{ newton-meter}^2/\text{coulomb}^2$$

Charges may be accumulated by friction and may be ***induced*** by electrical forces. The ***electroscope*** is an instrument for detecting charge. Charges move easily in conductors and with relative difficulty in insulators. Flowing charges (usually electrons) are electric ***current***. Electrostatic generators, such as the Van de Graaff generator, are designed to accumulate electric charge.

The ***potential difference*** in ***volts*** between two points is the number of joules of energy per coulomb that must be given to a charged particle to move it from one point to the other against an electrical force. The potential difference between a point and the earth is called the ***potential*** of the point. Electric cells transform chemical energy into electric energy. The electromotive force of a cell (the potential difference when there is no current) depends only on the chemicals in the cell. Several cells in series are called a ***battery***.

A potential difference between two ends of a conductor gives rise to a current. The current unit, one ***ampere***, is one coulomb of charge per second passing a section of the conductor. Steady cur-

rents ordinarily exist only in complete circuits. The current is the same at all parts of an unbranched circuit.

The electric *resistance* of a conductor is

$$\text{Resistance} = \frac{\text{potential difference}}{\text{current}}$$

The unit of resistance is the *ohm.* The resistance of a uniform conductor depends on the material and the dimensions according to the following:

$$\text{Resistance} = (\text{resistivity of material}) \frac{\text{length}}{\text{area}}$$

Ohm's law states that the resistance of a metallic conductor is a constant if the temperature is constant.

QUESTIONS

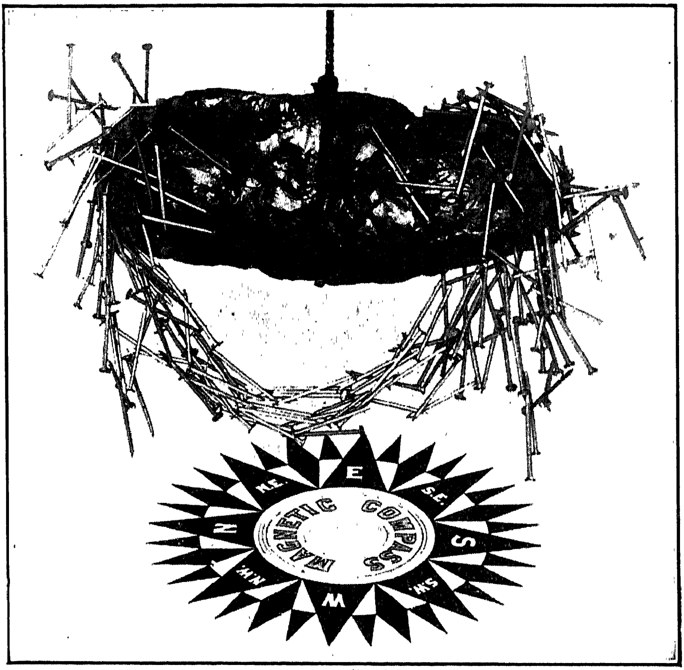
1. Why do we say that the electric charge on glass rubbed by silk is positive and that the charge on hard rubber rubbed by fur is negative?
2. What does Coulomb's law state about the force exerted by one charge on another? Is this force repulsive or attractive?
3. Explain the action of a gold leaf electroscope. How can it be used to demonstrate the existence of induced charges?
4. What are the elementary units of positive and negative electricity? What actually moves in the case of current in a metallic conductor?
5. What is the Van de Graaff generator? How is it operated?
6. What is electric potential difference? How is the unit defined? Why is potential difference a more useful quantity than potential?
7. Describe the action of a dry cell. Of a lead storage cell. What does the latter actually store?
8. What is the importance of Ohm's law? Is the statement $R = V/I$, without any qualifications about R, an experimental relation?
9. What is the current in a metal wire in terms of the charge on an electron? Why is a potential difference in a complete circuit essential for establishing a current?
10. The potential difference between the two wires in the wiring system of most American homes is usually maintained at about 120 volts. How much current will there be when an electric iron with a resistance of 20 ohms is connected to the wires?

CHAPTER X

ELECTRIC AND MAGNETIC ENERGY

MAGNETS

Legends from many lands reveal that the strange ability of certain rocks to attract iron was known far back in antiquity. According to one of these fanciful tales, a shepherd (of variable nationality) named Magnes was tending his herd when the nails

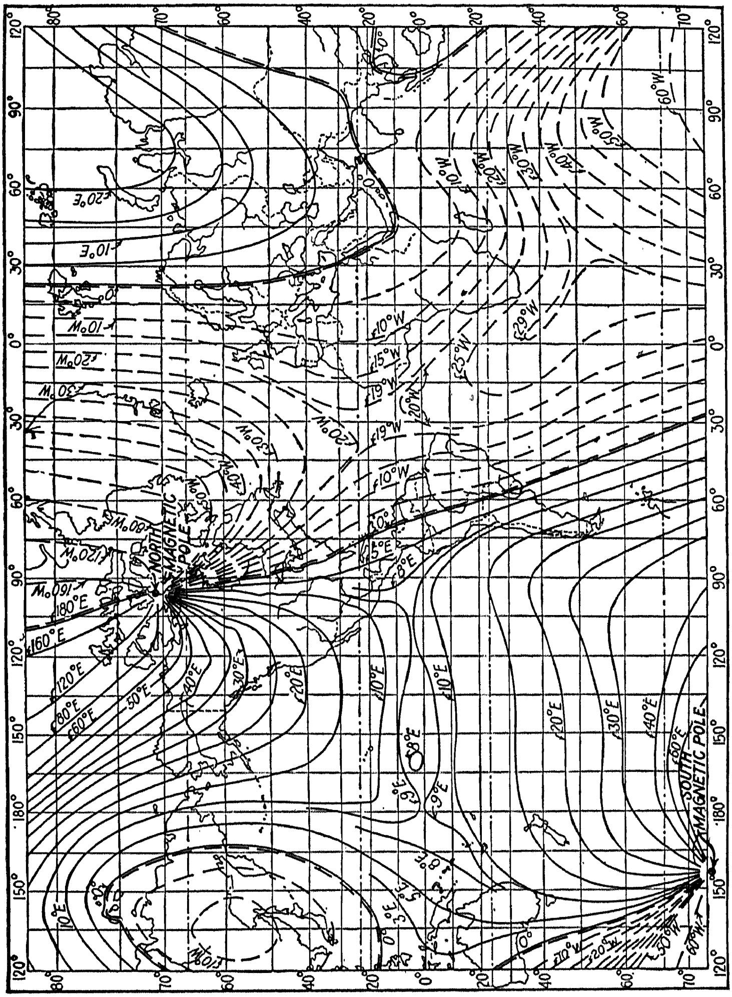


(*English, Getting Acquainted with Minerals.*)

Fig. 198. Magnetic effects of a lodestone.

in his shoes and the iron tip of his staff were held to a certain spot of ground. The rock responsible for this mysterious force was unearthed and called magnes after its discoverer. This name has come down to us as ***magnet,*** and the word ***magnetism*** expresses the ability to exert forces at a distance on a piece of iron.

The Chinese were probably the first to suspend such magnetic rocks from fibers so that their tendency to orient in a north-south direction could be used for navigation. These ***lode stones,*** or "leading stones," are now known to us as ***magnetite*** (Fe_3O_4), an iron ore.



(Department of Terrestrial Magnetism, Carnegie Institution, Washington.)

Fig. 199. Magnetic map for 1930. On each line the compass declination (angle between the needle and true north) is constant. The lines gradually shift in position since the earth's magnetic field is fluctuating continually.

The Earth Is a Magnet. That end of a suspended magnet which tends to point northward is called, in this country, the ***north pole,*** and the opposite end, the ***south pole.*** As early as 1600, Gilbert realized that the reason for the north-south orientation of a magnet must be that the earth itself is a giant magnet. The unlike poles of magnets

tend to attract one another, while like poles tend to repel. It follows that the earth actually has its magnetic "south" pole in the northern hemisphere, for this pole attracts what we call the "north" pole of a magnet. Columbus was disturbed during his voyage to

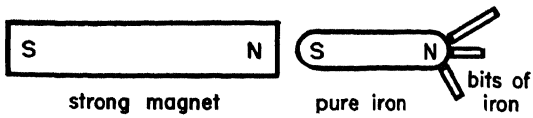


Fig. 200. Induced magnetism.

America because his compass needle did not always point in the true north-south direction. Actually, the direction of a compass needle varies considerably at different points on the earth's surface, and in the Arctic Ocean north of Canada the "north-seeking" end points southward! The reason for this deviation is that the earth's magnetic pole is in northern Canada, and not at the north pole of the earth's axis. Since the correction which must be applied to a compass reading to give true north is now known for all localities, sea and air navigators can use the compass to find the true north-south direction in any region.

Magnetic Materials. When a piece of iron is brought near a lodestone or another strong magnet, magnetism is ***induced*** in it, and it becomes capable of attracting other iron pieces. The part of the iron next to the north (N) pole of the magnet becomes a south (S) pole, and the farthest end becomes an N pole. If the iron piece is very pure, it loses its acquired magnetism when removed from the vicinity of the strong magnet. If, however, the iron piece has a small proportion of certain impurities, and especially if it has been subjected to hardening processes, it retains some of the induced magnetism and becomes itself a ***permanent magnet.*** Nickel and cobalt also show magnetic effects, but much weaker ones than iron.

Recently considerable research has been directed toward finding special alloys that have relatively great induced magnetism and others that retain a large proportion of the magnetism induced. There has been much success, particularly when the alloys are heated and cooled in special ways. A nickel and iron alloy (24 per cent Ni, 76 per cent Fe) called Permalloy becomes magnetized much more easily than iron itself when in a region near a magnet,

but retains very little of its magnetism when removed. Alloys of cobalt and iron are remarkable for the way they retain magnetism; thus they make much better permanent magnets than the older steels. More recent developments are alloys, such as Alnico, contain-

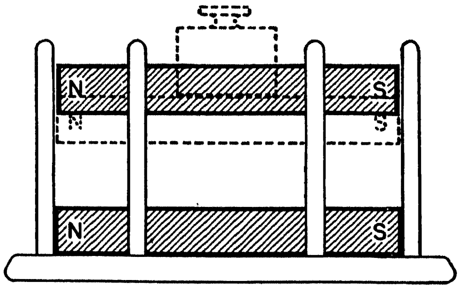


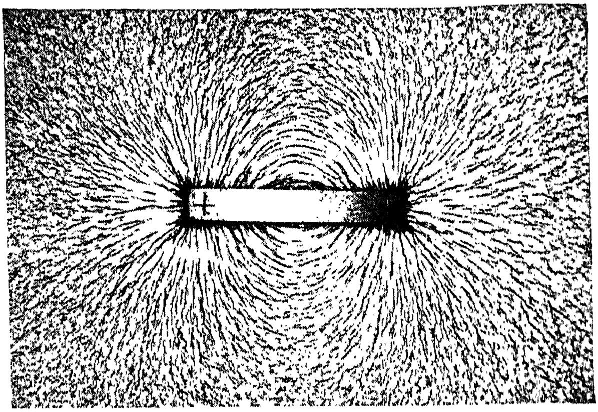
Fig. 201. Wobbly bar—upper bar magnet (in suitable guide) is supported by repelling force of lower bar magnet.

ing nickel and aluminum, the latter nonmagnetic by itself. These are very effective as permanent magnets. They readily lift many times their own weight; in fact, when one such magnet is placed above another with like poles over like, and with small guides to keep it from moving sidewise, it will float in space supported at a distance by the force exerted by the lower magnet.

Fields—Magnetic, Electric, and Gravitational. When two magnet poles are in the same region, they exert forces on each other, repulsive forces if they are like poles, attractive forces if they are unlike. We say that a ***magnetic field*** of force exists in the region about each of the poles; that is, any magnetic pole there would experience a force proportional to the ***field strength.*** The variation in strength and direction of the magnetic field about a bar magnet can be seen very easily by placing a piece of paper over the magnet and sprinkling iron filings on top. The tiny filings become magnetized by induction and tend to form little chains from pole to pole. These are said to show the direction of the "lines of force" in the magnetic field. What seems to be empty space definitely contains energy, for the iron particles placed in it experience forces which move them.

Similarly we say that an electrostatic field exists around an electric charge because a force is exerted on another electric charge brought near. Likewise, we say that a gravitational field exists around a body that has mass, for any other mass in the

neighborhood experiences a force. We learned earlier that electrostatic and gravitational force fields obey inverse square laws, as pointed out by Coulomb and Newton. Magnetic fields were found to behave in a similar fashion, because the force that one



(*Smyth and Ufford, Matter, Motion and Electricity.*)

Fig. 202. Magnetic field about a bar magnet. Shown by iron filings.

magnetic pole exerts on another is inversely proportional to the square of the distance between them.

It should be pointed out that the inverse square law cannot be tested as directly in the case of magnetic poles as for electric charges because an isolated magnetic pole does not exist. An attempt to cut the N pole off a magnet fails because each piece turns out to be a magnet complete in itself with N and S poles of equal strength. So the most nearly isolated pole obtainable would be on the end of a very long magnet with the matching pole far away. In using the simple, though somewhat artificial, picture of individual magnetic poles, care should be taken that both poles of every magnet are being considered.

Strictly speaking, all three kinds of force fields, gravitational, electrostatic, and magnetic, exist throughout all space, but because of their rapid decrease with distance they are strong only near their sources. Even so, electric and magnetic fields radiated from radio stations may be detected many thousands of miles away. Again the similarity between the three apparently different kinds of phenomena points to the yet unfathomed possibility of an underlying relation between them.

What Causes Magnetism? There has been much inquiry into the source of magnetism, and in the end all clues lead to the molecules and the atoms of the magnetic materials. Actually, all materials are magnetic, although most are only about one-millionth as magnetic as iron. Most atoms appear to be tiny magnets themselves, some much stronger than others. In normal materials the atomic magnets are oriented more or less at random, and their effects usually cancel each other. In the case of iron particularly, each tiny atomic magnet, when placed in a magnetic field, tries to line up with the field. When many more of the atomic magnets are lined up in one direction than in any other, their effects add, so the whole piece may become a very powerful magnet. When iron is heated dull red the tendency of the atoms to line up is so disturbed that no magnetism can be found. This might be taken to show that atomic grouping, which is broken up easily by high temperature, has something to do with pronounced magnetism.

An example of queer magnetic properties is provided by oxygen. The oxygen in our air is only very feebly magnetic, but when it is liquefied at low temperature (−182°C) it becomes magnetic and will climb right out of its container onto the poles of a powerful magnet.

MAGNETIC FIELDS FROM ELECTRIC CURRENTS

For many years men thought that there must be some connection between electricity and magnetism, but the proof escaped discovery for a long time. After the pioneer work of Volta and Galvani, increasingly powerful batteries were gradually developed, and thus it became possible to have larger and larger currents in wire. Finally in 1819, Hans Christian Oersted, then Professor of Physics at Copenhagen, discovered the long-sought relation. When he happened to bring a compass near a wire which was carrying a current, he saw a feeble motion of the compass needle. Quickly he tried various experiments which showed the nature of the magnetic field produced by the current.

Magnetic Field about a Current. If compasses are placed around a vertical wire in which there is a current they point as in Fig. 203. If iron filings are sprinkled on a glass plate through which passes a wire carrying a current, the filings distribute themselves in circles around the wire. *A magnetic field is produced by an electric cur-*

rent, that is, by *moving* electric charges. The "lines of force" are circular if the wire has a circular cross section, and lie in planes

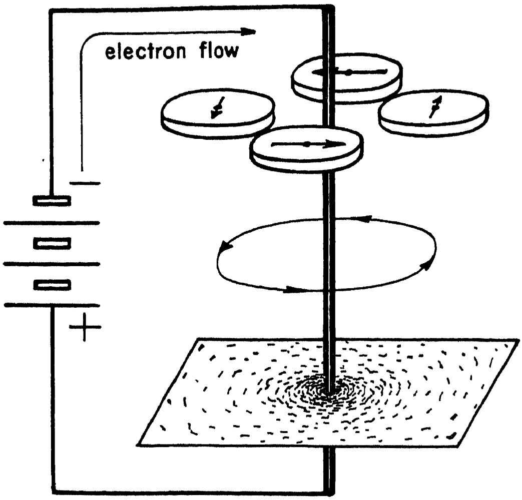
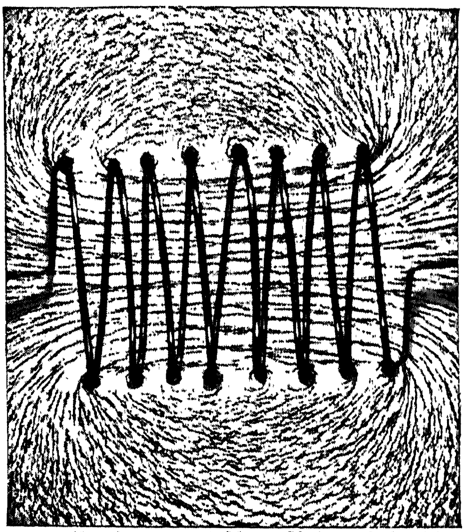


Fig. 203. Magnetic field about a wire carrying a current.



(*Smyth and Ufford, Matter, Motion and Electricity.*)

Fig. 204. Magnetic field of a solenoid carrying a current. Shown by iron filings.

perpendicular to the current. From the directions of the compass needles when the negative electrons flow as in Fig. 203, it can be seen that the magnetic field is directed as indicated by the ring of

arrows. The strength of the field is directly proportional to the current in the wire.

Magnetic Field of Current in a Coil. When a wire is coiled into a long series of turns (sometimes called a solenoid) and there is a

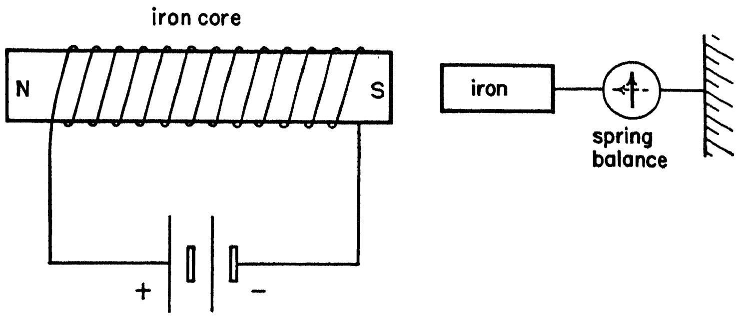


Fig. 205. Simple electromagnet.

current in the wire, the representation of the field as shown by iron filings looks very much like that of a bar magnet (Fig. 204).

Electromagnets. Joseph Henry, who was at Princeton University from 1832 to 1846, was one of the first to show that the

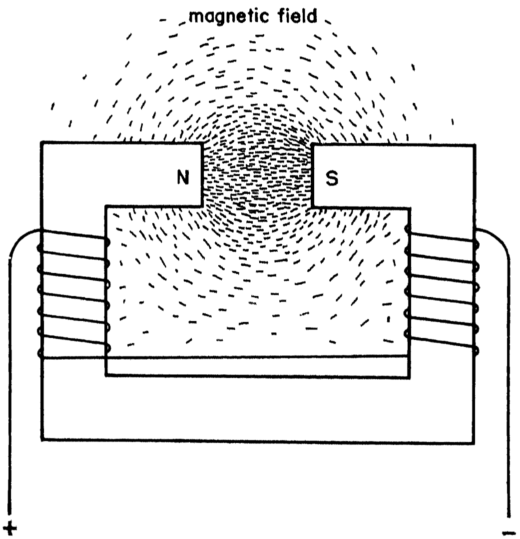
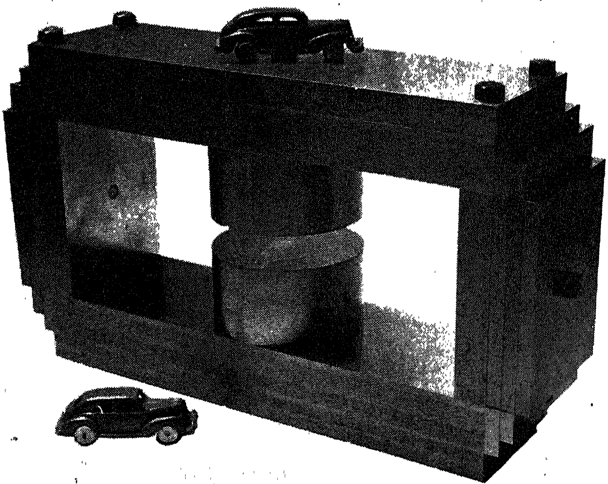


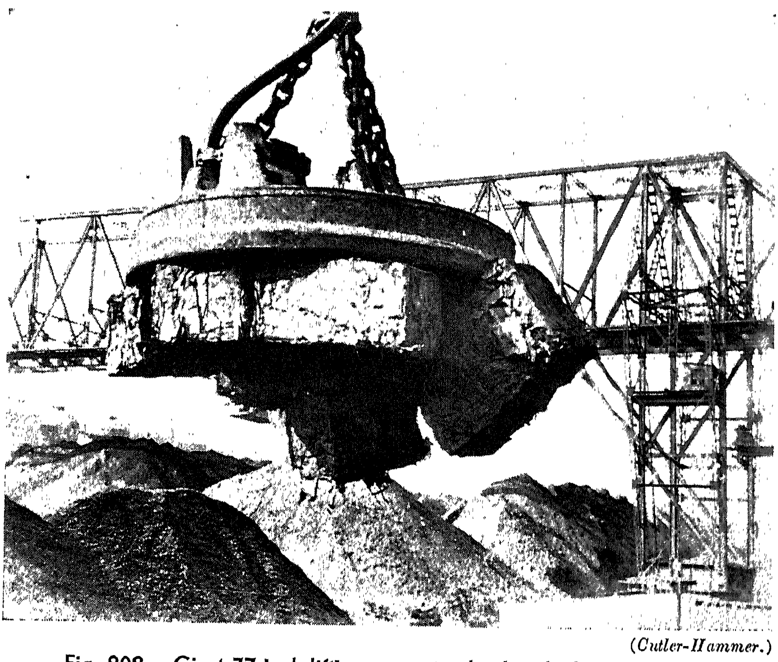
Fig. 206. Common type of electromagnet.

strength of the magnetic field produced by current in a coil could be tremendously increased by winding the coil on iron. When the elementary atomic magnets within the iron line up with the field of the coil, their superimposed effect adds to the original field, and



(*Donald Cooksey.*)

Fig. 207. Model of iron yoke for 4,000 ton magnet of cyclotron under construction at the University of California. Copper coils go on the two cylindrical pole pieces.



(*Cutler-Hammer.*)

Fig. 208. Giant 77-inch lifting magnet unloading bailed scrap iron from Great Lakes freighter.

the result may be several hundred times as great as from the coil alone. The field strength of the electromagnet can be increased further by arranging a more complete iron circuit so that the magnetic "lines" travel largely through iron. Common forms of modern electromagnets are indicated in Figs. 206, 207, and 208.

Electromagnets can produce magnetic fields much larger than those of permanent magnets. In other words, after magnetization in a powerful electromagnet the residual field remaining with a permanent magnet is usually small compared to the maximum field during the magnetization. There is a definite upper limit to the degree to which iron can be magnetized, even when used in electromagnets. Once all the elementary atomic magnets are lined up within the iron, not much further increase in magnetism can be obtained, and the iron is said to be ***saturated.*** Special alloys offer some increase in saturation magnetization over that of pure iron.

Out of Tiny Forces. Nearly all the great advances in science have grown out of effects at first so small that they were barely observed. Oersted could scarcely detect the motion of a compass needle when his feeble batteries set up a current through the wire. Step by step, forces of the kind that produced this motion have been increased so that modern electromagnets sometimes lift many hundreds of tons.

Another still more important development has grown out of Oersted's discovery. A wire carrying a current exerts a force on a near-by magnetic compass needle. But, according to Newton, every force has an oppositely directed twin acting on the body exerting the original force. It follows that a ***wire carrying a current experiences a force when placed in a magnetic field.*** Out of that first feeble force on Oersted's compass have grown all the electric motors which convert electric energy into mechanical energy on an ever-increasing scale in our homes, farms, and industries. Let us see how this development has come about.

Force on a Wire Carrying Current in a Magnetic Field. If the wire of Fig. 209 is suspended loosely in the strong magnetic field, and a current is set up in it, the wire jumps toward the reader. If the battery connections are changed so the current through the wire is reversed, the wire is forced in the opposite direction. ***The force on a wire carrying a current is perpendicular both to the magnetic field and to the current.*** This mutual perpendicularity

between the three directions of *force, field,* and *current* is characteristic of relationships between mechanical, magnetic, and electrical phenomena. The magnitude of the force depends, as one might expect, on (1) current, (2) the strength of the magnetic

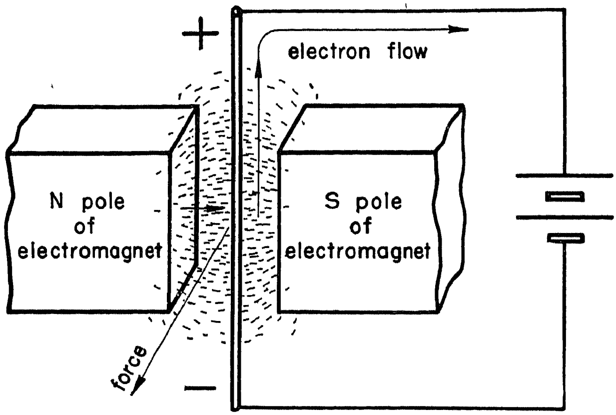


Fig. 209. There is a force on a wire carrying a current across a magnetic field. The force is directed perpendicular both to the current and to the direction of the magnetic field.

field, (3) the length of the wire in the field. In fact

$$\text{Force} \propto \text{current} \times \text{magnetic field strength} \times \text{length}$$

Because the force, current, and length can be measured readily, this expression (instead of that for the force on a magnet) is used now to define the unit of magnetic field strength.

Causing Rotation. In order to make electromagnetic forces useful, it is convenient to arrange that they produce continuous rotation. Suppose that we suspend a single loop of wire between the pole pieces of a magnet and produce a current in the wire (Fig. 210). In the left-hand part of the loop the direction of current is such that the force is directed toward the reader. In the right-hand part, the current is opposite, so the force is directed away from the reader. These equal and opposite forces make the loop of wire *rotate.* The effectiveness of forces in producing a twist is called the *torque,* which in this instance is the *product* of one of the *forces* and the *distance* between the two forces. Another way of saying this is that when the loop carries a current it behaves like a small magnet (it is, indeed, the simplest possible electromagnet) and its N and S poles tend to line up with those of the large magnet. As might be expected from what we have learned about the force

on a straight wire, each of the forces which tend to rotate a loop of wire carrying a current in a magnetic field is proportional to the current, to the magnetic field strength, and to the total dimensions of the loop perpendicular to the field.

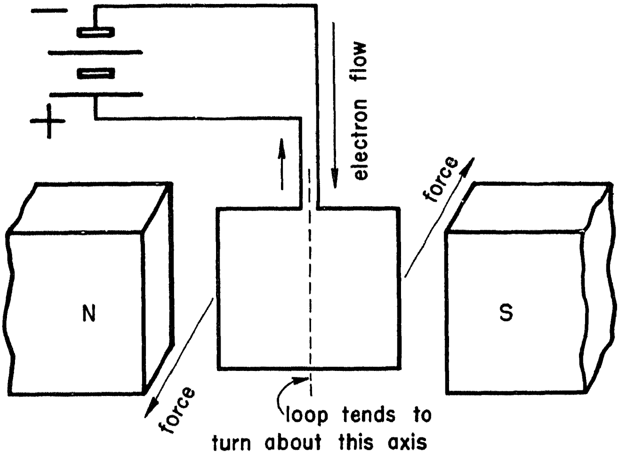


Fig. 210. There may be a torque on a loop carrying a current in a magnetic field.

Force $\propto$ current $\times$ magnetic field strength $\times$ length of wire perpendicular to field

These forces and the width of the loop determine the torque which produces the rotation.

The tendency of a loop of wire in a magnetic field to rotate when a current is in it is the basis of most of our meters which measure current and voltage, and of most of our electric motors which transform electric energy into mechanical energy.

ELECTRICAL MEASURING INSTRUMENTS

Measuring Current. Less than one hundred years ago it was a difficult matter to measure an electric current. The French physicist d'Arsonval was one of the first to suggest that meters to measure current could be made very simply. He placed a loop of wire in a magnetic field and took as a measure of a current in the loop the accompanying torque which tended to rotate the loop. As we know, the torque in such an arrangement is proportional to current.

Galvanometers. Very sensitive current-measuring instruments are called galvanometers. In order to make an instrument ex-

tremely sensitive, many turns of fine wire coiled into rectangular form are used rather than a single loop, for the torque is proportional to the total length of wire perpendicular to the field. A permanent magnet is commonly used to produce the magnetic

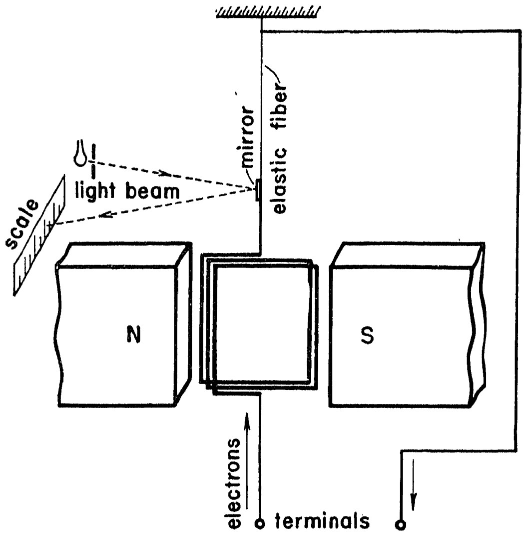


Fig. 211. Diagram of galvanometer.

field. The coil is suspended on a fine conducting fiber so that only a small resisting torque is exerted by the fiber when the coil is rotated. This torque is proportional to the angle of rotation, and a current in the coil produces a rotation until the torque exerted by the fiber equals the torque exerted by the magnetic field. The amount of rotation thus measures the current once the instrument is calibrated. A light metal pointer attached to the coil can be used to measure the deflection on a scale, but when high sensitivity is desired, a weightless light beam reflected to a scale from a tiny mirror mounted on the coil makes a splendid "pointer."

Modern galvanometers are so sensitive that currents as small as 10^{-11} amperes can be measured!

Ammeters. Ammeters are simply rugged galvanometers. Careful efforts to achieve high sensitivity are not necessary when large currents are to be measured, and ruggedness is often more important than sensitivity. Coils are usually mounted on jewel bearings rather than by fragile fibers, and light metal pointers are used to indicate deflections. Light springs keep the pointer at

"zero" and provide the resisting torque which is proportional to the deflection. This torque balances the torque produced by the magnet when there is a current in the coil.

When moderate or large currents, say 0.01 to 10,000 amperes,

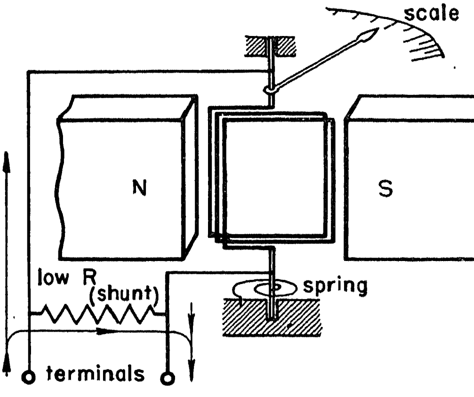


Fig. 212. Diagram of ammeter. There is usually a low resistance shunt arranged so that only a small fraction of the total current passes through the coil of the instrument.

are to be measured, a low-resistance wire called a ***shunt*** is placed across the terminals of the ammeter coil so that most of the current goes through the low resistance, and only a small fraction goes through the coil of the meter. An ammeter measures the current in a circuit and so must be placed in ***series*** with the rest of the circuit. In order not to disturb the current in the circuit, it is desirable that the ammeter have as ***low resistance*** as possible. It will ***always*** have some resistance and, therefore, when inserted in the circuit, will always reduce the magnitude of current somewhat, but this reduction is small enough to be neglected in ordinary practice.

Voltmeters. Measuring the electric potential difference between two points means measuring the tendency to make electrons move through a circuit connecting the two points. If the resistance of the circuit is known, measurement of the current in it is sufficient to give the voltage.

Voltmeters make use of the same type of moving coil system as ammeters. In the voltmeter, however, a high resistance is placed in ***series*** with the moving coil. When the voltmeter is connected ***across*** a dry cell, or to any other two points between which the

potential difference V is to be measured, the current I responsible for the rotation of the coil is, we recall

$$I = \frac{V}{R}$$

Here R is the total resistance of the voltmeter (the series high

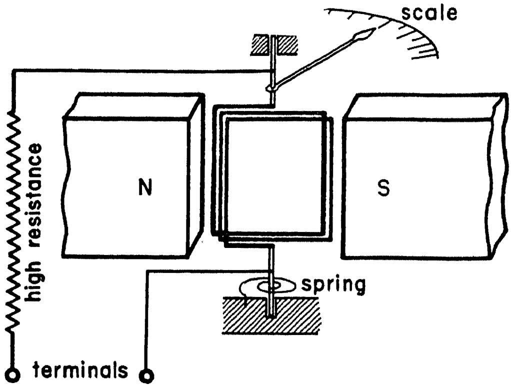


Fig. 213. Diagram of voltmeter. There is usually a high resistance in series with the coil of the instrument so that it takes relatively little current from the circuit across which the voltage is measured.

resistance plus the resistance of the coil itself). The reading of the voltmeter, therefore, is proportional to the potential difference V, so the meter can be calibrated in terms of V.

A good voltmeter should take as little current as possible, that is, have as high resistance as possible, for the current that it takes when used to measure potential differences in an electric circuit always changes the thing that the voltmeter tries to measure.

The fact that the use of an electrical measuring instrument always upsets, to some extent, the very condition that is to be measured is a serious fundamental difficulty. In reality every attempt to observe phenomena in nature always results in changing the phenomena concerned. This raises some interesting experimental and philosophical questions. Sometimes the changes are small enough to be quite negligible, but when we try to measure smaller and smaller things the reaction of the act of observation on the thing observed becomes very important. We shall see[1] that, when we try to measure quantities associated with things like

[1] See Chap. XVIII on the Heisenberg uncertainty principle.

individual electrons, considerable *uncertainty* in each measurement is inevitable.

MEASURING ELECTRIC ENERGY

The development of simple, sensitive, and reliable electrical measuring instruments is associated in a major way with the great advances in the comprehension and application of electric energy in the past fifty years. Here, as in every field, quantitative measurements are essential for real progress. Until they can be made, scientists can furnish little more than vague ideas.

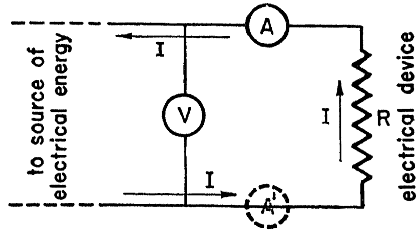


Fig. 214. How to connect an ammeter (A) and a voltmeter (V) to measure the current through a resistance and the voltage across the resistance. It makes no difference whether the ammeter is placed at A or A′ since the current is the same at all points in a simple series circuit.

Volts, Amperes, and Ohms. What happens when you plug in an electric toaster, or nonchalantly flip a switch and flood a room with light? Now that we have some understanding of electrical instruments, we can make use of them to help us answer questions of this sort. Of course, we hardly expect to become electrical engineers, but we ought to understand at least a little about the calculations which have been linked with the use of electrical phenomena.

The difference in potential between the two terminals of sockets and outlets in residences in the United States is usually maintained by the power plants at about 110 to 120 volts. There is *no* current unless some sort of electrical appliance is connected to the two terminals. If an electric heater, a lamp, an electric iron, toaster, stove, or similar device is connected to the two terminals, the magnitude of current depends on both the voltage V between the terminals and the resistance R of the device

$$I = \frac{V}{R}$$

A convenient schematic representation of such a connection is given in Fig. 214. By placing an ammeter A in *series* with the electrical device R, the current in it can be measured. It makes no difference on which side of R the ammeter is placed, for the current is the same everywhere in a simple unbranched circuit. A voltmeter

V placed ***across*** the device gives the potential difference between its terminals. In some appliances used with alternating current another factor called ***inductance*** must be considered (Chap. XVI), but for electrical devices such as those mentioned this effect need not be taken into account.

With a common electric heater plugged into the outlet, the voltmeter of Fig. 214 might read 120 volts (the line voltage) and the ammeter 5 amperes (amp). From this we know that the resistance R of the heater is

$$\frac{120 \text{ volts}}{5 \text{ amp}} = 24 \text{ ohms}$$

Resistances in Parallel. What happens when we plug in both the heater and a desk lamp? This arrangement, including voltmeter

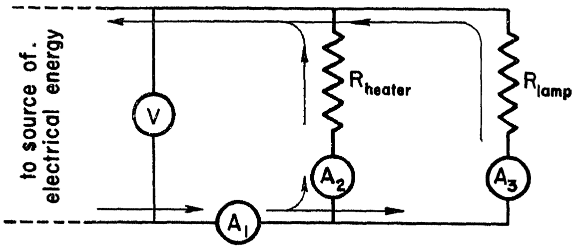


Fig. 215. The total current to resistances in parallel is the sum of the currents in the separate resistances. The same voltage is across each resistance.

and ammeters, is indicated schematically in Fig. 215. The voltmeter reads nearly the original 120 volts if the power lines are of low resistance and the generators maintain constant line voltage. There might be 6 amp in the ammeter A_1, 5 amp in A_2, and 1 amp in A_3. This sharing of the total current by the lamp and heater is to be expected. As indicated by the arrows, the total current from the line (6 amp) is divided so that 5 amp of it is in the heater, and the remaining 1 amp is in the lamp. The heater takes the same current that it did when connected alone, because the applied voltage is the same. The currents in the lamp and heater reunite once more and then are directed back toward the power plant. The ammeter readings 5 and 1 add to 6 amp, the total current. The lamp resistance must be

$$R_{\text{lamp}} = \frac{120 \text{ volts}}{1 \text{ amp}} = 120 \text{ ohms}$$

Sometimes it is convenient to think of two resistances in parallel (such as the electric heater and the desk lamp) as being equivalent to one resistance (Fig. 216). Experiments show that in such a setup the two resistances are equivalent to a resistance R which may be calculated from

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

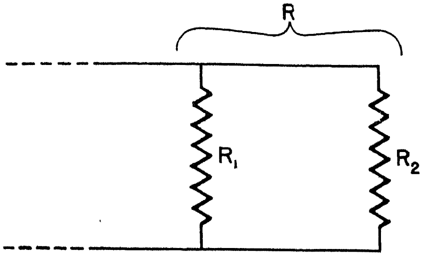


Fig. 216. Resistances in parallel. The effective resistance of the combination is less than the value of either resistance alone.

In the case of the heater and the lamp

$$\frac{1}{R} = \frac{1}{24} + \frac{1}{120} = \frac{6}{120} = \frac{1}{20}$$

so the equivalent resistance is R = 20 ohms. Across 120 volts a 20-ohm resistance would take a current of 120 volts/20 ohms = 6 amp, which, of course, is just what we found originally to be the total current.

Resistances in Series. Another common type of circuit is that of two or more resistances in series, so that all the current from the

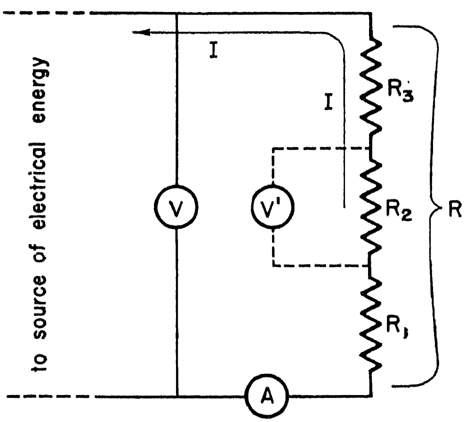


Fig. 217. The total voltage across resistances in series is the sum of the voltages across the separate resistances. There is the same current through each resistance.

source of electric energy must be through each of the resistances in turn. This is illustrated in Fig. 217. As there are no branches for a part of the current to follow, it is clear that the current in each of the resistances is the same. The three resistances act as though they

were equivalent to a single resistance R equal to the sum of the individual resistances, so

$$R = R_1 + R_2 + R_3$$

Suppose that $R_1 = 10$ ohms, $R_2 = 20$ ohms, and $R_3 = 30$ ohms. They are then equivalent to $10 + 20 + 30$, or 60 ohms. If the voltmeter reads 120 volts, then the ammeter reads

$$I = \frac{V}{R} = \frac{120 \text{ volts}}{60 \text{ ohms}} = 2 \text{ amp}$$

If we connect a voltmeter, first across R_1, then across R_2, and then across R_3, the sum of the "potential drops" across the resistances will be 120 volts. Ohm's law tells us what the voltmeter will read in each of these cases. The voltage

across R_1 will be $V_1 = I\,R_1 = 2 \text{ amp} \times 10 \text{ ohms} = 20$ volts,
across R_2 will be $V_2 = I\,R_2 = 2 \text{ amp} \times 20 \text{ ohms} = 40$ volts,
across R_3 will be $V_3 = I\,R_3 = 2 \text{ amp} \times 30 \text{ ohms} = 60$ volts.

The sum of the voltage drops is $20 + 40 + 60 = 120$ volts, which is just the total line voltage. Thus, the total potential difference is accounted for.

Physicists and electrical engineers are often required to predict what will happen in circuits much more complicated than these, but extensions of the same simple principles we have used make it possible to tell accurately what will occur.

Electric Power and Energy. Energy and power, we have learned, are nearly always the most important factors in physical phenomena. When there is a current in an electrical device which is essentially a resistance, such as a lamp, heater, or toaster, the electric energy is all converted into heat energy. Of course we wish to be able to estimate the energy output of such appliances, and the easiest way is from the electric energy input.

Energy. Electric energy is determined in much the same way as is mechanical potential energy. The potential energy changed to other forms when a body of weight W or mass m falls through some distance h is given (see page 208) by

Potential energy $= Wh$ or mgh, in ft-lb or joules (newton-meters)

Similarly, the electric energy changed to other forms when an electric charge Q "falls" through a difference of potential V (that

is, passes from one point to a point V volts lower in potential) is given by

$$\begin{aligned}\text{Electric energy} &= \text{electric charge} \times \text{difference in potential}\\ &= QV \text{ joules}\end{aligned}$$

Actually, we seldom measure electric charges directly. Instead, we measure the current I, which is the rate of flow of electric charge, and obtain the total charge passing a section of the circuit in t seconds by using the relation

$$Q = It$$

which applies if I does not change. If V also is constant, the quantity It may be put in place of Q in the expression for electric energy, so we can say

$$\text{Electric energy} = VIt \text{ joules}$$

This is usually a convenient expression for electric energy.

Because electric energy is transformed readily into heat energy in resistances, it is often useful to know the number of kilocalories of heat energy generated when a steady current I is in a resistance R for t seconds. The electric energy transformed into heat energy is

$$VIt = RI^2t \text{ joules}$$

because the potential difference between the two ends of a resistance is $V = RI$ volts. Now we know (page 237) that

$$4{,}186 \text{ joules} = 1 \text{ kcal}$$

so the energy transformed into heat is

$$\begin{aligned}RI^2t \text{ joules} &= \frac{RI^2t}{4{,}186} \text{ kcal}\\ &= 0.00024RI^2t \text{ kcal}\end{aligned}$$

Power. When you read the label on an electric lamp bulb you may see 120 volts, 60 watts. When the current is "switched on," electric energy is changed to heat energy in the filament of this lamp at the rate of 60 watts or 60 joules/sec. When the filament is heated at this rate it reaches such a high temperature that it radiates light. As this suggests, it is often convenient to know how much *energy per second* (in watts) is being used, that is, *power* (page 221).

From our ideas about electric energy we can see that if V and I are constant

$$\text{Power} = \frac{\text{energy}}{\text{time}} = VI \text{ watts (joules/sec)}$$

The unit of electric power is named the *watt* in honor of James Watt, who developed one of the first practical steam engines.

Electric power can be expressed in several ways in terms of resistance, current, and potential difference. We know that $V = IR$, or $I = V/R$. So:

$$\text{Power} = VI = I^2R = \frac{V^2}{R} \text{ watts}$$

In any simple electric circuit the power dissipated in a resistance can be obtained by measuring the two quantities in any one of these expressions. Of course all three relations give the same answer, but sometimes it is more convenient to measure the voltage and current, and other times the current and resistance, etc.

If we use a 120-volt, 60-watt electric lamp we know that the current must be

$$I = \frac{\text{power}}{V} = \frac{60 \text{ watts}}{120 \text{ volts}} = \frac{1}{2} \text{ amp}$$

The amount of electric energy used obviously depends on the time that the light or other device is "on." The energy unit we have been using

$$1 \text{ joule} = 1 \text{ watt} \times 1 \text{ sec}$$

is actually rather small for most practical purposes. If the 60-watt lamp burns for 1 sec, 60 watt-seconds of energy are used. In 1 hr (3,600 sec), 21,600 watt-sec are involved. You can see that in an average residence, with many electric lamps and other appliances, a tremendous number of watt-seconds of energy will be used in a month.

Kilowatt-hours. When you pay the bill for electric energy to the power company you pay for a certain number of ***kilowatt-hours***. This larger unit is used in order to avoid a number which looks like the national debt for expressing ordinary electric energy consumption. The kilowatt is 1,000 watts, and the hour 3,600

seconds, so

$$1 \text{ KWH (kilowatt-hour)}^1 = 3.6 \times 10^6 \text{ watt-sec or joules}$$

The average residential consumer uses about 100 KWH of electric energy per month. The consumption is increasing steadily, for new devices are being added continually to the average home: radios, refrigerators, electric razors, washing machines, dish washers, higher power lights to secure better illumination, and even air-conditioning units.

FOR STUDY AND READING

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SUMMARY

Magnets exert forces on magnetic material. A free magnet orients generally north-southward; hence it has ***north*** (N) and ***south*** (S) poles. Unlike poles mutually attract and like poles repel; so the earth is a magnet with its S pole in the northern hemisphere.

Iron in which magnetism is ***induced*** may remain a ***permanent*** magnet if it has certain impurities. Nickel and cobalt are weakly magnetic, and certain iron alloys are magnetized more easily than iron.

In the ***magnetic field*** about any magnetic pole, another pole experiences a force that is inversely proportional to the square of the separation. Actually every magnet has N and S poles of equal strength. Free small magnets orient along ***lines of force*** of a magnetic field.

An electric current has a magnetic field encircling it, with a ***field strength*** proportional to the current. By coiling a wire carrying current, the magnetic field may be concentrated, and it may be intensified further by placing iron in the coil.

A straight wire carrying a current across a magnetic field experiences a force perpendicular to the field and the current and

[1] 1 KWH = 2.66×10^6 ft-lb.

proportional to the current, the field strength, and the length of wire in the field.

A wire coil carrying a current tends to rotate in a properly directed magnetic field. This is used in most meters that measure current or voltage; there, an elastic suspension or a spring makes the amount of rotation proportional to the current in the coil.

An ***ammeter,*** frequently with a ***shunt,*** is placed in series with the current to be measured. A ***voltmeter*** is connected to the two points between which a voltage is to be measured. It has a high resistance, so the current in it is proportional to the voltage. These instruments upset somewhat the quantities they measure.

The current in an ordinary appliance is the ratio of the voltage across the appliance to its resistance. Two resistances (R_1 and R_2) in ***parallel*** have an effective resistance R given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

The effective resistance of any number of resistances in ***series*** is the sum of their values.

In an appliance with applied voltage V and a steady current I, the electric energy changed to heat in t seconds is VIt joules or $0.00024VIt$ kcal. The power is energy/time $= VI = I^2R = V^2/R$ watts. Electric energy is usually measured in kilowatt-hours, and 1 kilowatt-hour $= 3.6 \times 10^6$ watt-seconds or joules.

QUESTIONS

1. What is a magnet? Why must care be taken in considering effects of an individual magnetic pole?
2. Why does a suspended magnet become oriented in a generally north-south direction? How is this phenomenon related to the mapping of the field of a magnet by iron filings sprinkled on a paper over the magnet?
3. What are magnetic, electric, and gravitational fields? What do they have in common?
4. How are electromagnets usually constructed?
5. What quantities determine the magnetic field produced by a current in a wire?
6. How do we use the force on a conductor carrying a current in a magnetic field to measure current in a simple galvanometer?
7. On what factors does the sensitivity of the suspension-type galvanometer depend? What sets a limit to the obtainable sensitivity?
8. Why is it the usual practice to provide ammeters with a low shunt resistance, and voltmeters with a high series resistance?
9. Is it reasonable to expect that the ratio of the voltage across a conductor to current in it should be constant over a wide range of current values?
10. What energy unit appears on your monthly bill from the electrical company?
11. A 1,000-watt heater and five 100-watt lamps are plugged into a 120-volt house line. What should be the minimum fuse rating?

12. What is the total effective resistance of the combination in question 11? How does this compare with the individual resistances?
13. At 5 cents per kilowatt-hour, how much does it cost to operate the heater and lamps of question 11 for three hours?
14. At 120 volts, what resistance should be put in series with a 1,000-watt heater to reduce its power consumption to 500 watts?
15. What is the effective resistance of 10 ohms, 15 ohms, and 20 ohms in parallel? In series? What current would be taken by each of these combinations across 120 volts? How much power would be dissipated?

CHAPTER XI

PUTTING ELECTRIC ENERGY TO WORK

Electric Motors. As soon as it was known that there is a force on a wire which carries a current across a magnetic field, many attempts were made to construct motors to convert electric energy to mechanical energy. As early as 1823, tiny crude motors were constructed which would actually revolve. The only available sources of electric energy were feeble voltaic chemical cells, so only about one "fly-power" was obtainable. Motors of large power had to wait until large electric energy sources were developed.

There is little real difference between electric motors and moving coil galvanometers, except that motors are usually much larger and must be arranged so that the coil can rotate freely and continuously. In a galvanometer, as soon as a current is set up, the coil becomes like a tiny magnet, and if the coil were mounted freely on bearings it would simply rotate and come to rest with its N and S poles lined up with the opposite poles of the fixed "field" magnet. The moving coil is called the ***armature.*** To change the galvanometer to a motor the armature coil must be made to rotate continuously. For this purpose, a switching arrangement called a ***commutator*** is provided, so that the current through the armature coil is reversed just as the coil comes in line with the fixed "field" magnet poles. The coil is then magnetized so that it rotates still more in order to line up with the opposite poles. This is repeated again and again, producing continuous rotation of the armature coil. The current always is reversed at just the proper time to carry on the rotation of the coil.

Actual motor armatures usually have several coils, of many turns of wire wound on an iron core, to provide large magnetic forces. The commutator consists of copper segments insulated from one another and connected to the coils. The current is carried to the armature coils by spring contacts called ***brushes*** against which rub successive pairs of the commutator segments.

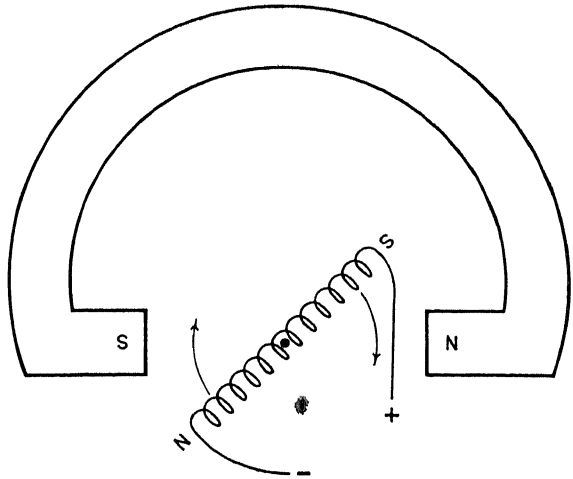


Fig. 218. A solenoid carrying a current, like any magnet, tends to line up with a magnetic field.

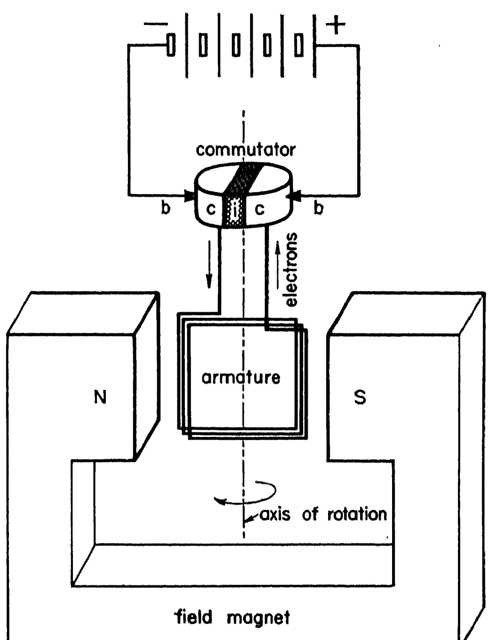


Fig. 219. Principle of a DC motor. The commutator reverses the direction of current in the coil at the proper times to maintain rotation. The commutator consists of copper segments (c) separated by an insulator (i). Contact with the commutator is made by the brushes (b) pressing against its surface.

The fixed magnetic field usually is made by sending some of the current from the electric energy source into ***field coils*** wound on iron cores. When the field coils are placed in parallel with the armature coils, as in Fig. 220, the motor is called a ***shunt*** motor.

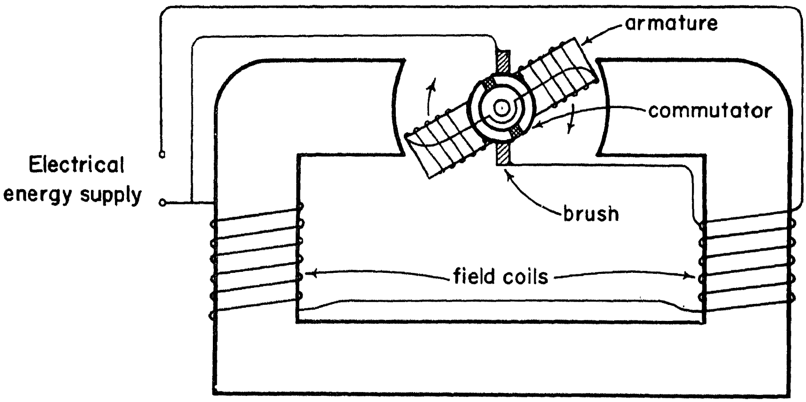


Fig. 220. Simple DC motor.

This is the usual connection for large ***direct-current***[1] (DC) motors. When the field coils are placed in series with the armature coils, the motor is called a ***series*** motor. Most small motors, such as those on ordinary electric fans which can be used on either alternating or direct current are of the latter type.

Converting Electric Energy to Mechanical Energy. In addition to simplicity of transmission, one of the great advantages of electric energy is the ease and efficiency with which it can be converted into other forms of energy. Electric motors are being used more and more widely to do all sorts of tasks in the home, on the farm, and in industry—from sweeping floors and pumping water to operating huge stamp presses, lathes, and spinning mills. Aside from the convenience, comparative simplicity, and cleanliness of electrically operated machinery, one of the major reasons for its extensive use is its high efficiency.

Of course, electric motors are no exception to the statement that man has not yet developed machines which are 100 per cent efficient. The copper wires in the field and armature coils have resistance, R, and when there is current, I, through these wires, the electric energy converted into heat during a time t always equals I^2Rt joules. Then, too, the bearings on which the armature

[1] As contrasted with alternating current, p. 320.

shaft rotates have friction, and wind resistance at high speed is not negligible. Some energy also is "lost" in magnetizing and demagnetizing the iron cores. In designing a motor to do a certain job, electrical engineers have to compromise between efficiency,

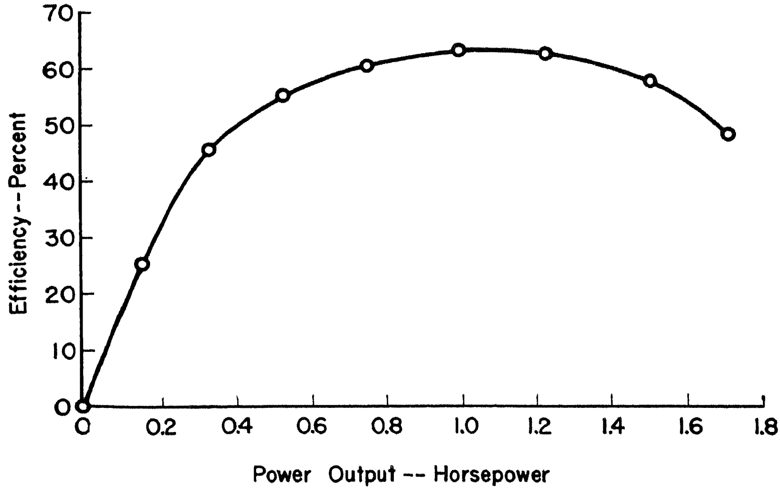


Fig. 221. Performance of a 1-hp shunt-wound motor.

size, weight, and cost. The resistance of the windings can be decreased by using copper wires of increased diameter, but this increases the motor's size, weight, and cost.

We know that

$$\text{Efficiency} = \frac{\text{output energy}}{\text{input energy}}$$

In electric motors this also is (output power)/(input power), because the time involved for the output is exactly that for the input. Both power input and power output can be measured readily. The electric power input is

$$VI = \text{line voltage} \times \text{current}$$

The mechanical power output, (*force* $\times$ *distance*) *per second,* or force $\times$ speed, can be measured at the same time as the input by causing the motor to rotate a pulley against a known force, or load, while the pulley surface is moving at some measured speed.

A typical record of efficiency plotted against power output, for a motor which had been tested, is shown in Fig. 221. The motor in this case was labeled 1 hp by the manufacturer. Of course, when

there was no load on it, that is, when it was "running idle," no useful work was done, so the efficiency was zero. The efficiency increased as the motor was called upon to deliver more mechanical power, reached a maximum of about 65 per cent near the rated power input, and began to decrease rapidly as the motor became "overloaded." Very large motors of 25 to 100 hp often have efficiencies reaching 90 per cent or more.

Tireless servants created as the result of man's understanding, electric motors are but one more example of the way in which mastery of nature, ***properly used,*** can be made to free man from mere brute labor.

PRODUCING ELECTRIC ENERGY

Michael Faraday. Probably no one man contributed more to our electrical age than Michael Faraday (1791–1867). A blacksmith's son, he first learned of physics through books sent to the book bindery where he was apprenticed. His persistent interest led Sir Humphry Davy to give him the job of bottle washer in the laboratories at the Royal Institution. Twenty years later he succeeded Davy as Director of the Royal Institution. Faraday made many contributions to physics and chemistry, among them the discovery of the laws of electrolysis and descriptions of many electrostatic phenomena, but it is chiefly for his discovery of the relation between electricity and magnetism that we honor him.

Faraday was an experimenter of the first order. Not by nature a theorist or a mathematician, he preferred to account for phenomena to his own satisfaction by means of simple pictures. An example is the concept of "lines of force" which has been so useful in describing magnetic fields.

He became intensely interested in Oersted's demonstration of the mechanical forces on conductors carrying current when in magnetic fields, and in work of Ampère which showed the existence of forces between wires which carry current. An electric current in a magnetic field sets up a mechanical force; so, Faraday reasoned, it should be possible somehow to ***produce*** electric currents by magnetic fields. For a long period he worked with magnets and coils endeavoring to verify this belief.

Finally, in 1831, he discovered the solution. A coil was connected to a galvanometer. When the current in a second coil near by was started or stopped, Faraday's trained eyes saw a momentary

flicker of the galvanometer needle. It was a ***changing*** or ***moving*** magnetic field that set electric charges in motion. Faraday had discovered ***electromagnetic induction,*** and, in so doing, he ushered in the era of electric power.

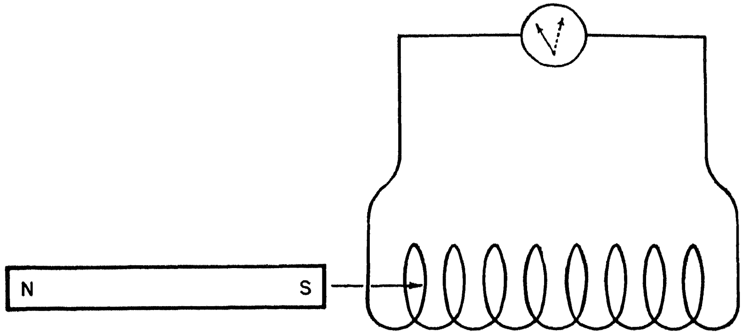


Fig. 222. Moving the magnet in or out of the coil induces a momentary current only when the magnet is in motion.

Step by step this first feeble flicker has been magnified until there has evolved our whole system of production and distribution of electric energy. In Faraday's time probably no one could foresee from this barely detectable effect the great central power stations or utilities industries of today. In fact, to most people, Faraday doubtless seemed an impractical putterer playing with wires and magnets.

Electromagnetic Induction. Let us consider some simple experiments which show the essential ideas in Faraday's discovery. If an ordinary coil is connected to a galvanometer and a magnet is pushed into the coil, the galvanometer pointer deflects suddenly, showing a current, but it returns quickly to its zero position when the magnet is held at rest inside the coil. If we pull the magnet out of the coil, the pointer deflection is in the ***opposite*** direction, but becomes zero almost immediately. ***No current whatever is observed in the coil when the magnet is at rest. Only moving or changing magnetic fields "induce" electric currents.*** Of course we can move either the magnet or the coil. Thus we observe that mechanical energy can be converted into electric energy by moving the coil and the magnet with respect to each other.

Now, instead of the magnet and a coil, let us use ***two coils,*** as Faraday did in his first experiment. When we close the switch and produce current in the first coil, a magnetic field grows quickly.

Its "lines of force" spread out and move across the wires in the second coil, much like ripples spreading out on a pond. This electromagnetic disturbance induces momentary currents in the second coil just as surely as if a permanent magnet or a coil carrying

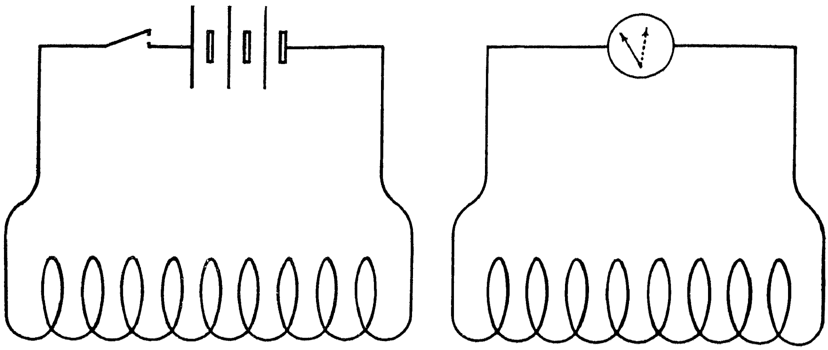


Fig. 223. Change of current in an electromagnet induces current in a nearby circuit.

a steady current had been moved with respect to it. The galvanometer pointer deflects and then returns quickly to zero. No current is observed in the second coil as long as the current in the stationary first coil is steady. When we open the switch and stop the current in the first coil, again there is a momentary current in the second coil, but in the opposite direction. ***Current is induced only when the current in the first coil is changing,*** that is, ***when the magnetic field produced by it is changing.*** Reversing the direction of the initial current, or turning one of the coils end for end, reverses the direction of current in the galvanometer.

The second coil must be subjected to a changing magnetic field if currents are to be induced in it. That changing field can be produced either by varying the current in a near-by stationary coil, or by actually moving the first and second coils with respect to each other. As we saw before, a relative motion between a permanent magnet and a coil produces the same result. One further fact is worth noticing. If the experiments of the last paragraph are repeated with the two coils placed on a single iron core, the induced currents in the second coil are many times larger than before. Iron greatly increases the magnetic fields produced by currents in the coils, and also "leads" the "lines of magnetic force" from the first through the second coil.

"Generating" Electricity on a Practical Scale. When a conductor is forced to move across a magnetic field, a voltage is induced in it, which, as we know, produces a current when the conductor is part of a complete circuit. By using strong magnetic fields and coils with

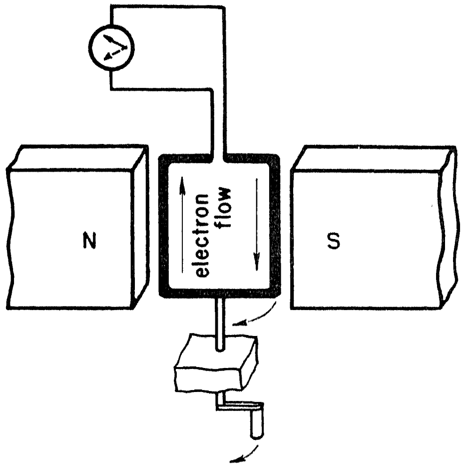


Fig. 224. Current is induced in a loop of wire rotated in a magnetic field.

many turns of wire, the induced voltages, and therefore the currents, can be made large. To get the maximum effect the conductors must be moved perpendicularly to the magnetic field. Actually, devices for producing electric energy from mechanical energy, or ***generators*** as they are popularly called, are almost exactly like electric motors of the type that we have considered.

Suppose that a single loop of wire is placed in a strong magnetic field and rotated by means of a torque applied to it with a handle or pulley (Fig. 224). The wire on the left moves in one direction through the magnetic field, and the wire on the right moves in the opposite direction. Therefore, the voltages induced in both wires set up currents in the same sense, which produce a galvanometer deflection, for example, to the ***right***. However, as the loop is rotated a half revolution further, the two wires exchange directions through the magnetic field, so the induced voltages are opposed to the earlier ones, and the galvanometer pointer deflects to the ***left***.

Alternating Current. The change in total voltage during one complete rotation is represented graphically in Fig. 225. The voltage starts at zero at position *A*, Fig. 225*a*, goes to a maximum in one direction (call it the "positive" direction) as the wires pass one set

of poles, and then decreases to zero a half revolution from position A. As the armature loop is rotated further and the wires pass the opposite set of poles, the voltage reverses and becomes a maximum in the opposite direction, then becomes zero once more as the loop

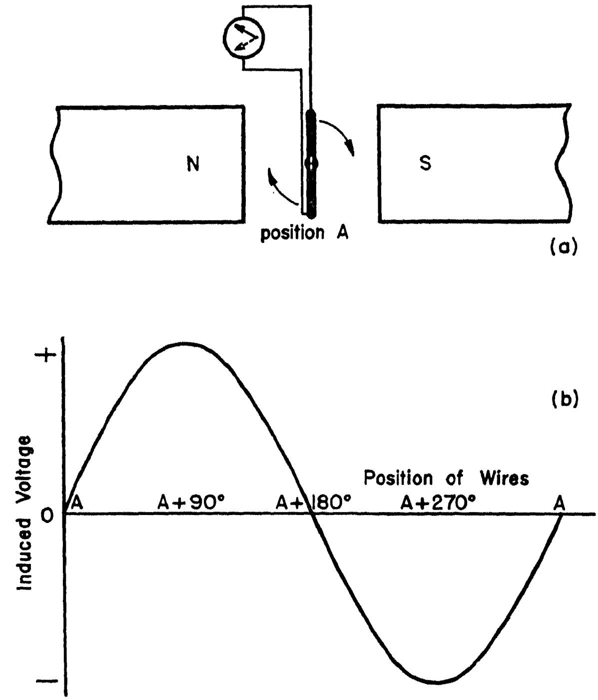


Fig. 225. Character of the voltage induced in a wire loop rotated in a magnetic field.

returns to position A. This type of generator gives an alternating positive and negative voltage, resulting in a current first in one direction then in the opposite, so we call it an *alternating-current* (AC) generator. The number of complete *cycles per second* is, of course, the *frequency* of oscillation of the voltage. It may seem surprising that a generator of this type, but of course with more complex armature and field coils, is in many ways more useful than one in which the voltage, and therefore the current, is always in the same direction.

Direct-current Generator. In order that the voltage and the current from a generator be in one direction only, there is introduced a commutator-brush switching arrangement exactly like that on a direct-current motor. This reverses the connections to the

armature at the proper times so that the current will always be in the same direction. By providing several armature coils of many turns of wire on an iron form and connecting them to commutator segments and by using electromagnets to supply the fixed ***magnetic***

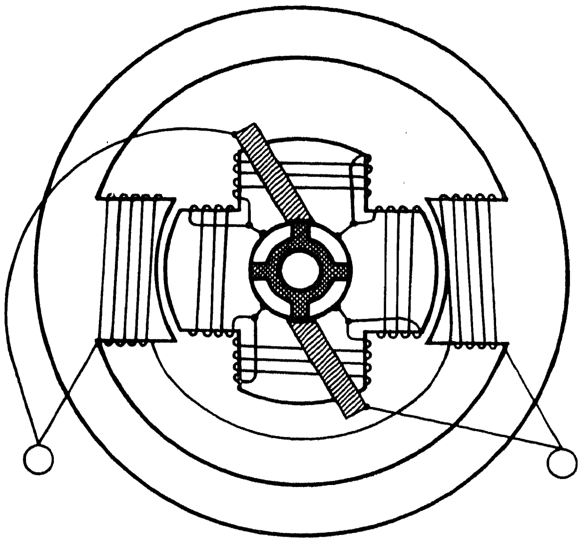


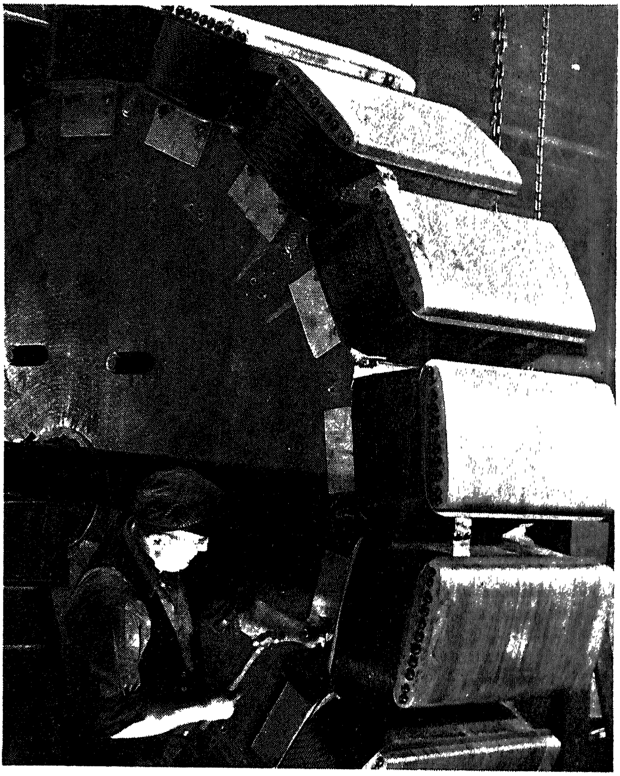
Fig. 226. DC generator. This could also serve as a DC motor (Fig. 220). Omitted for simplicity, another pair of field coils and brushes would permit use of both sets of armature coils at the same time.

field, in short by making an exact duplicate of the direct-current motor, a comparatively steady ***direct current*** can be produced when the armature is rotated.

Mechanical to Electric Energy. In rotating the armature of a generator, mechanical energy is converted into electric energy. In operating a motor, electric energy is converted into mechanical energy, so the motor and the generator perform operations which are exactly the converse of one another.

Naturally the amount of electric energy produced by a generator can never quite equal the mechanical energy input. If the terminals of a generator are not connected to any circuit, electric "pressure" or voltage is produced, but as there is no current the electric power (volts × amperes) is zero. Then the only mechanical energy required is that to overcome mechanical friction. If, however, electric lamps or other electrical devices are connected to the terminals, the voltage produces current in them and the generator

supplies electric energy. Then the mechanical energy required to rotate the generator increases by at least an amount equal to the electric energy output. We don't get "something for nothing" with a generator, nor do we ever actually *make* electricity. The



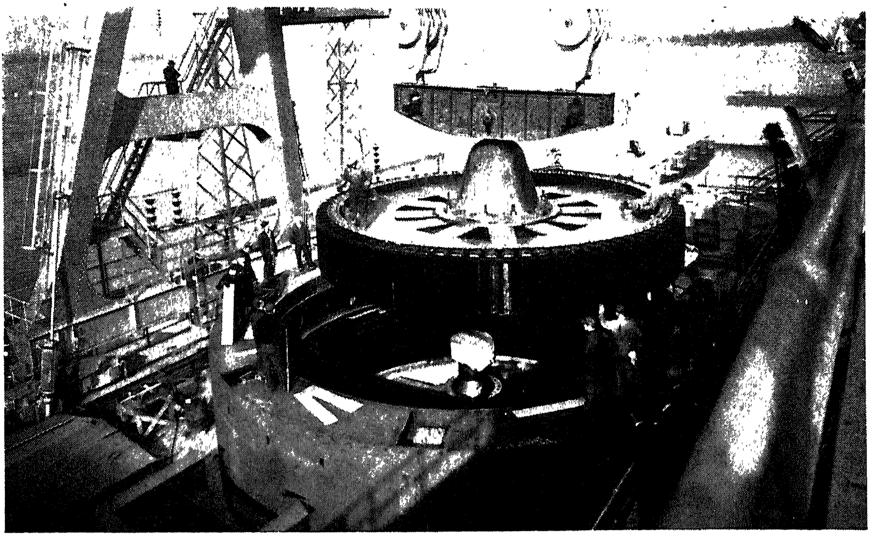
(*Westinghouse Electric and Manufacturing Company.*)

Fig. 227. Rotor of medium size generator to be powered by a waterwheel.

electrons with their negative electric charges were always present in the wires, and all the generator does is to set them in motion.

The generator in a power plant is much like a pump, in that it forces electrons to circulate through the conducting power lines, to pass through our electrical appliances where they do work producing heat, light, or whatever we will, and then to hurry back to the power plant.

As soon as methods for converting mechanical energy to electric energy on a large scale were available, the production and distribu-



(*Power.*)

Fig. 228. Installation of generator rotor. Rotor of 450,000 lb being lowered into 36,000-KW generator at Wheeler Dam.

tion of electricity for use got under way to commence our "age of electrification."

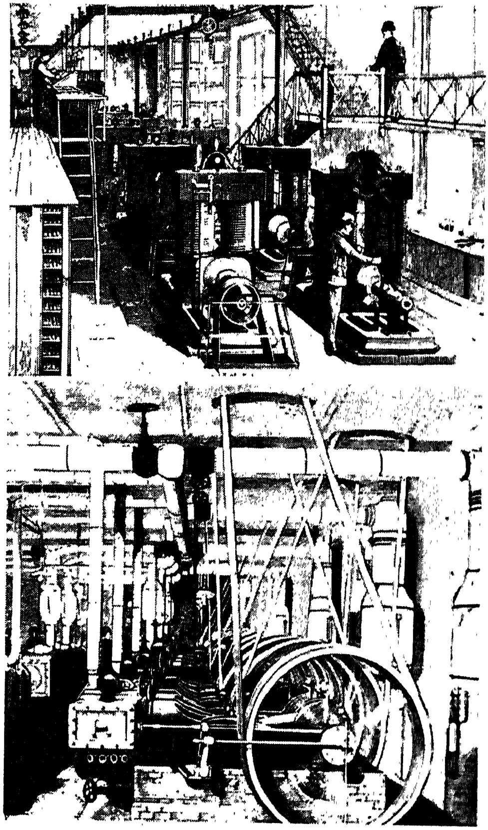
TRANSPORTING ELECTRIC ENERGY

Transmission Lines. Giant steam turbines or oil engines in central stations, or efficient water turbines at sites of great dams, produce the mechanical energy to turn the huge generators of today. In order to make practicable the transportation of electric energy over the great distances from these generating stations to users it has been necessary to find ways of reducing energy losses in power transmission lines.

For most residential and industrial uses, comparatively small potential differences, about 110 to 120 volts and in some cases 220 to 240 volts, have been most practical. Higher voltages than this would add many serious difficulties with insulation and increase the hazard to life from shock.

In the 1880's, when Thomas Edison and other pioneers installed low-voltage, direct-current generators in the old Pearl Street station in New York and elsewhere, it was difficult to transmit electric energy far with reasonable efficiency. Resistance, which is always present in power lines, produced serious effects. Even near the powerhouse, the old Edison carbon filament lamps glowed none

too brightly, but at increasing distances they became dimmer and dimmer. Voltmeters at the power house might have read 120 volts, but a mile away they might have indicated only 90 volts. The current I in a power line with a total resistance R results in a



(*Consolidated Edison Company.*)

Fig. 229. Part of Edison's original Pearl Street generating station. This plant, the first steam-electric station, was placed in service in 1882.

voltage drop of IR between the beginning and end of the line. Consequently, as a line is lengthened, the voltage at the end drops because of the increased resistance. The power lines become warm because the electric power lost in lines, I^2R watts, goes to heating the wires and the surrounding air.

Reducing Energy Losses in Transmission Lines. One way of decreasing the energy losses in power transmission lines, in order to make more energy available for use at the end, is to decrease the

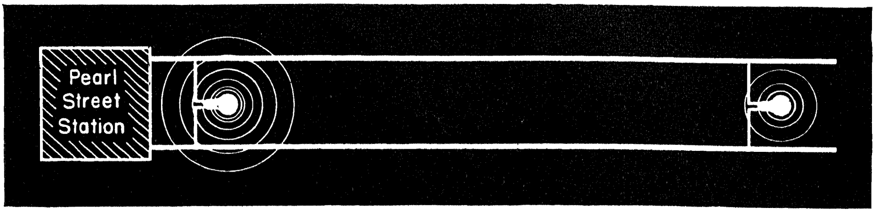


Fig. 230. Long lines could not be used efficiently in the old low-voltage DC transmission systems.

resistance of the copper conductors by increasing their diameter. With the voltages used in residences and shops, this method may be applied to short lines, but for long lines the cost of the copper, now 20 to 30 cents per pound fabricated, would be prohibitive.

There remains a more satisfactory solution to the problem of transmitting electric energy over considerable distances. If the transmission voltage is increased, the current required to carry the same power (VI) is correspondingly lower. The drop in voltage IR in the power lines is thus reduced. Still more important, the power loss in the lines I^2R, which is proportional to the ***square*** of the current, is greatly reduced. The first successful long-distance distribution of electric energy was made possible by the transformer and alternating current. Let us see how.

The Transformer. The secret of our present-day electric energy distribution is in the dark-gray or black boxes, large and small, which may be seen mounted on poles of transmission lines, or often in great banks outside power distributing stations.

The transformer grew out of the experiment of Faraday, in which a changing current in one coil induced a current in a near-by coil. To produce this effect, it is actually much simpler to use alternating current rather than interrupt a direct current, for alternating current is continually changing and so is continually inducing voltage in near-by wires. We recall that ***no induced effect whatever is produced by a steady direct current.***

In modern form, a transformer usually consists of two coils of wire wound on a core of iron strips. The iron, as we have seen, serves to guide a magnetic field from one coil through the other coil. Suppose that one coil, called the ***primary,*** is connected to a source of alternating current, say a generator which gives alternating current with a frequency of 60 cycles per second (60-cycle AC, for short). Then the voltage across the primary coil increases

from zero to a maximum value in $\frac{1}{240}$ sec, returns to zero in the next $\frac{1}{240}$ sec, increases to a maximum value in the opposite sense in the third $\frac{1}{240}$ sec, and then returns again to zero in another $\frac{1}{240}$ sec. The current follows the voltage through a similarly timed variation, continuously repeating the cycle every $\frac{4}{240}$ or $\frac{1}{60}$ sec (hence the term 60-cycle AC).

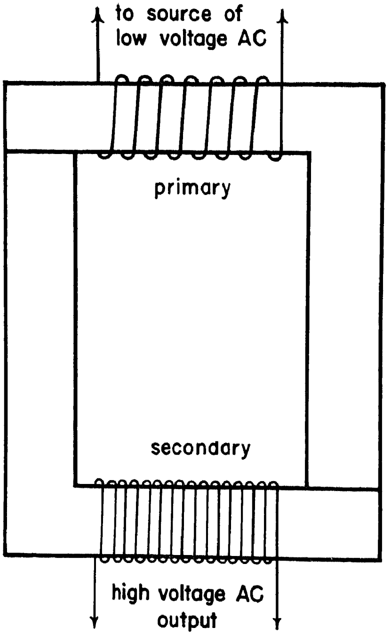


Fig. 231. Step-up transformer. Primary and secondary are wound on the same laminated iron core.

As the current in the primary coil reverses direction twice every $\frac{1}{60}$ sec, the magnetic field associated with this changing current sweeps back and forth across the other coil (the ***secondary***) at the same rate. Even though there exists no direct connection between the two coils, an alternating voltage is induced in the secondary coil.

Transformers as Voltage Changers. The importance of a transformer usually lies in its ability to "step up" or "step down" voltages. If we wish to have the voltage of the secondary 100 times that of the primary, we need simply provide 100 times as many turns of wire on the secondary as on the primary. Likewise, if we wish to have $\frac{1}{100}$ as much voltage across the secondary coil as the primary we merely provide $\frac{1}{100}$ as many turns on the secondary as on the primary. In other words, the ratio of the voltage across the primary to that across the secondary is the same as the ratio of the number of turns on the primary to that on the secondary.

No, we are not getting something for nothing just because voltages can be stepped up (or down) at will, for the ***currents are changed in the inverse ratio*** when power "losses" are negligible. If the voltage is stepped up by 100 times, the current will not be more than $\frac{1}{100}$ as great. The transformer is like a self-adjusting machine. Even though a voltage is induced in the secondary, there is no current whatever in the secondary unless it is connected to some device that completes the circuit. Also, the current in the

primary is nearly zero if no current is in the secondary. When current is taken from the secondary, the current in the primary increases correspondingly, so the electric power output and input are always in balance.

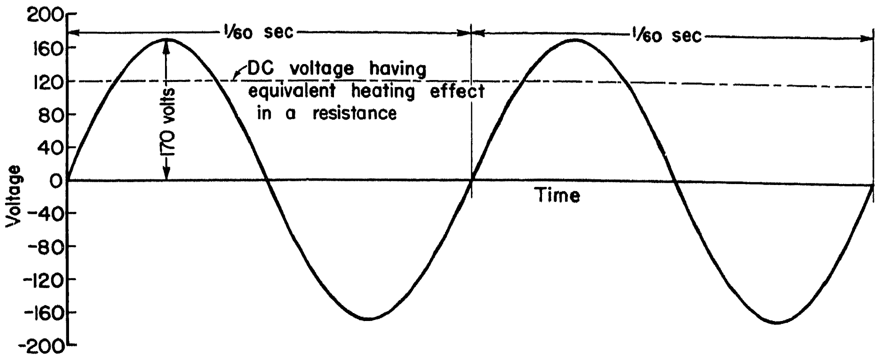


Fig. 232. Wave form of 120-volt, 60-cycle AC. One complete oscillation takes place in 1/60 sec. Thus there are 60 oscillations per second, hence the name "60 cycle." Note also that the amplitude must be nearly 170 volts in order that the heating effect be equivalent to that of 120-volt DC.

In general, for a transformer, $V_{\text{secondary}} \times I_{\text{secondary}}$ is always slightly less than $V_{\text{primary}} \times I_{\text{primary}}$.*

Like all machines, the transformer is never 100 per cent efficient, although good transformers often have efficiencies of 98 per cent. The copper windings do have some resistance and become warm, and some energy is transformed to heat in magnetizing and demagnetizing the iron.

Step-down Transformers. Some ideas about step-down transformers and the large currents that can be produced by them may be obtained from the transformer illustrated in Fig. 233. A primary winding of many turns is connected to the 120-volt AC lines. The secondary is a heavy, solid copper ring. Since it is only a single turn, a potential difference of less than a volt is induced in it, but its resistance is so small that the current may be thousands of amperes. The copper ring quickly becomes red hot and can even be melted. The ring experiences a large force because of the large current in it perpendicular to the magnetic field produced by the primary. In fact, if not held down, the ring is thrown many feet into the air!

* Actually, measurement of AC power is not so simple as that of DC power.

In addition to reducing the voltage from power lines, step-down transformers are used widely in homes to give 2 to 20 volts to ring bells or to run electric train motors and various toys. They are indispensable in processes where high currents are important, as in

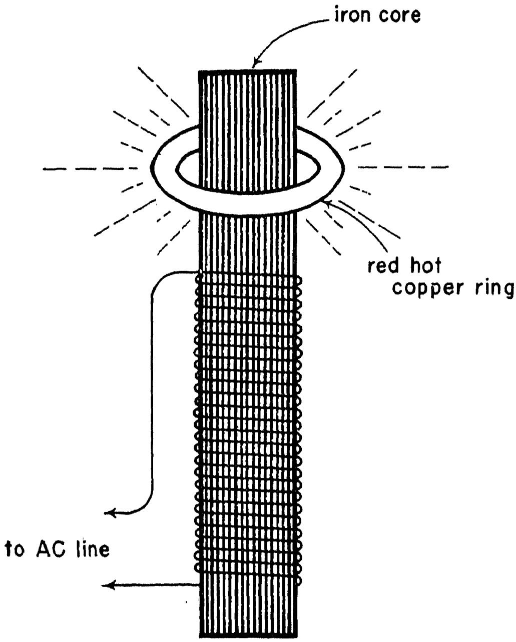


Fig. 233. Step down transformer. The single-turn secondary carries such a large current that it becomes red hot.

electric welding. For an electrically heated blanket which is becoming popular, in order to avoid any danger of shock, a low-voltage step-down transformer is used to provide the current in resistance wires woven into the blanket.

Step-up Transformers. Some of the possibilities of step-up transformers are suggested by a large transformer with few turns on the primary and many turns on the secondary, which can produce, say, 50,000 to 100,000 volts. When the primary of a transformer such as the one in Fig. 234 is connected to the alternating-current lines, great sparks many inches long jump across the "horn" gap between the ends of the secondary coil, at the place where the separation is least. The hot gases in the spark rise upward so that the spark may spread out to a length of more than a foot. Finally, however, the distance becomes so great that the

spark can no longer be maintained. It then breaks, only to be followed by another of the same kind. A continual succession of such sparks occurs.

You have probably seen "horn" gaps on power lines, for

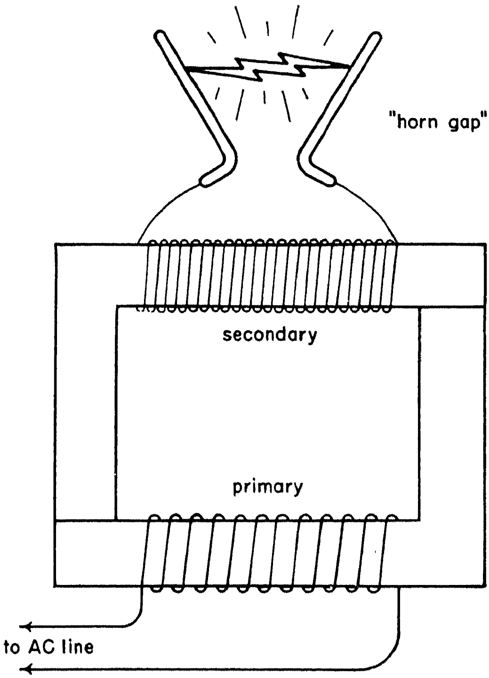
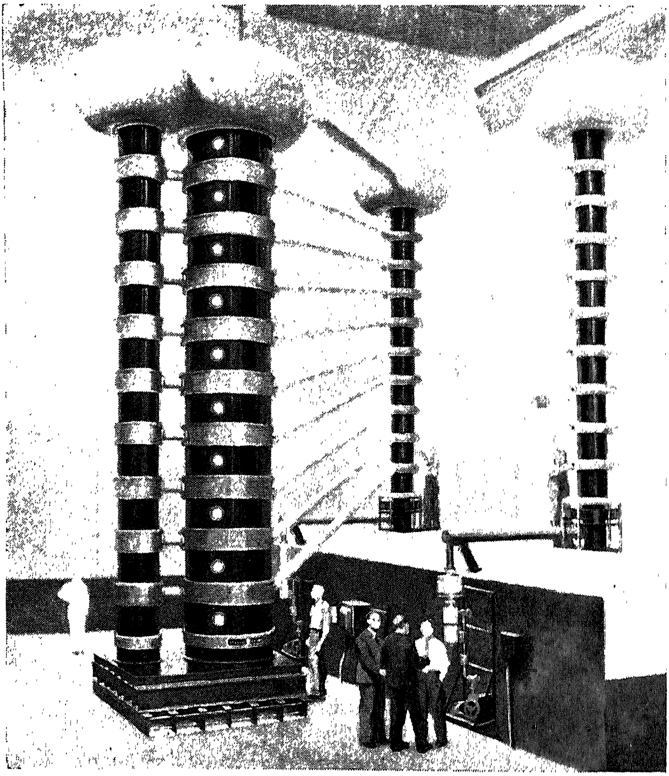


Fig. 234. Step-up transformer with "horn gap."

they are used widely as protection against lightning. One side of the gap is connected to the ground and the other to the power line, but the distance between is made so great that the normal power-line voltage will not cause a spark across the gap. When lightning strikes the power line a spark jumps the gap, harmlessly leading the surge of current to the ground. Then the spark quickly "blows itself out" and all returns to normal without any damage to transformer or other equipment.

If your radio set is on an alternating current line, it probably has a small transformer to step up the 120 volts AC of the line to 300 volts or more for use in the set (see Chap. XVII on radio). The all-too-numerous luminous gas signs, popularly called "neon" signs, are made to glow by the use of transformers giving small currents at 2,000 to 20,000 volts. Dentists' and doctors' X-ray

tubes commonly use transformers which give 50,000 to 250,000 volts. The new supervoltage transformers for production of penetrating X rays, for "atom smashing" and for industrial testing provide one to three million volts.



(*By H. M. Mott-Smith, courtesy of General Electric Company.*)

Fig. 235. 1,400,000-volt transformer-rectifier system and X-ray tube at National Bureau of Standards.

Step-up transformers in operation are usually very dangerous, so they must be treated with proper consideration. Some types, such as the transformers for luminous signs, are purposely made to deliver such small currents that they are not likely to produce a fatal shock, but all deserve the greatest respect.

Although usually quite harmless, ordinary 120-volt house lighting circuits can easily produce fatal shocks when the currents are allowed to reach vital nerve centers and disorganize the rhythmic heart action. Each year many people are killed needlessly as a result of foolishly touching "live" or poorly insulated electrical

fixtures, for example, while standing in bath tubs or in other places where their bodies are connected by a low-resistance path to the ground. A good fraction of these people could have been saved if *immediate* artificial respiration such as is used in drown-

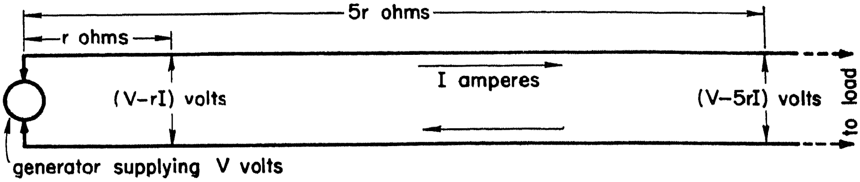


Fig. 236. Voltage drop along a transmission line. The indicated resistances include both wires of the line.

ings had been given them. It is usually possible to restart the rhythmic heart action very quickly, if only artificial respiration is begun within a few seconds, or, at most, a few minutes after the shock.

High-voltage, Low-current Transmission Lines. Now that we have thought about transformers, let us see how they are used to make possible the efficient transmission of electric energy.

As we saw earlier, in the days when low-voltage, high-current transmission was used, very little electric pressure remained at the end of a line of appreciable length because of the large voltage drop, IR, resulting from the high current in the line. Even worse, the power lost in the line, I^2R, was large, because that is proportional to I^2 (doubling the current gives four times the power loss). Such considerations are the same whether alternating-current or direct-current generators are used.

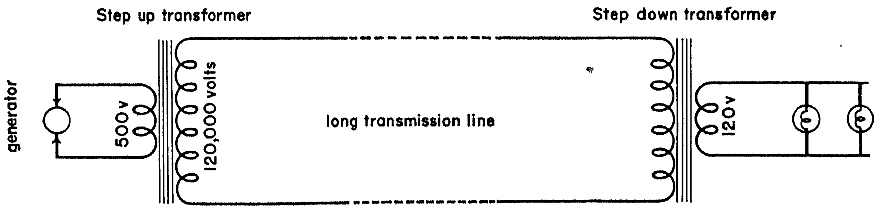
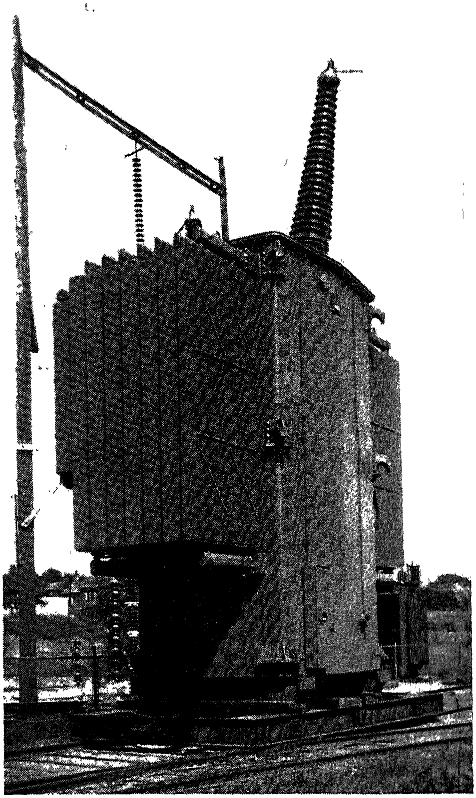


Fig. 237. Modern high-voltage, low-current transmission line.

In a modern transmission system, the voltage from the alternating-current generator, which may be 120 to 3,000 volts, is first "stepped up" to 12,000, 60,000, 120,000, or even 280,000 volts and then applied to the transmission line. The transmission line leads

to a distant point (or points) where electric energy is wanted, and there a step-down transformer is placed, to change the high voltage to low voltage, between 120 and 240 volts, to be distributed locally for residential or industrial purposes.



(*Westinghouse Electric and Manufacturing Company.*)

Fig. 238. Large transformer for use at Boulder Dam.

The currents in the parts of the distribution system are nearly inversely proportional to the voltages. They depend upon the currents in the lamps, motors, or other devices connected to the line through transformers, because, as we learned before, there is almost no current in a good transformer until devices that absorb energy are connected to it.

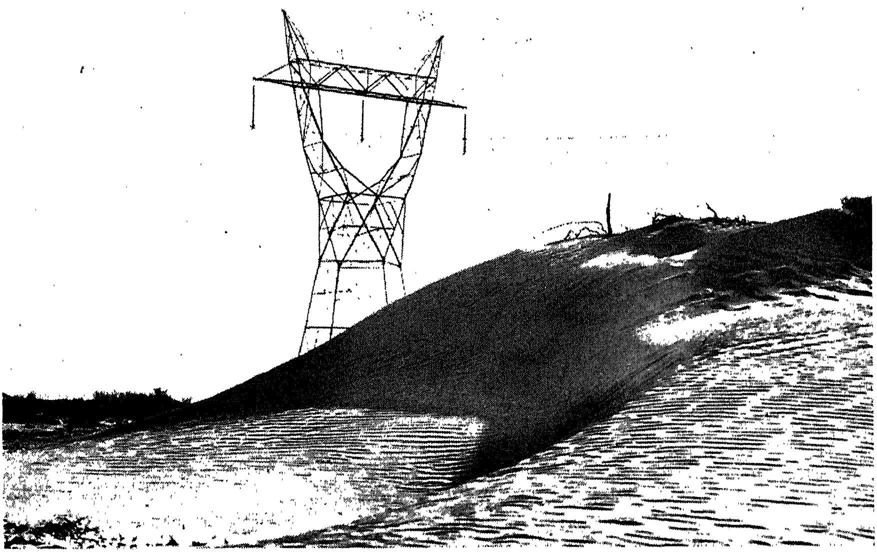
With 120,000 volts on the main line, stepped down by a factor of 1,000 to 120 volts for the local circuit, the currents in the line are about 1/1,000 as great as those in the low-voltage circuit. If

we compare this line with a low-voltage, high-current transmission line of the same size and resistance, such as we previously considered, the voltage drop, IR, in the high-voltage line will be only 1/1,000 as much as in the other. The power losses, I^2R, will be only $(1/1{,}000)^2$ or 1/1,000,000 as much!

The tremendous saving in energy with high-voltage, low-current lines is startling. No wonder the electrical industry grew rapidly after distribution systems of this type were developed. Clearly it is desirable to use as high voltage as possible. Gradually line voltages have been increased. The Boulder Dam line to Los Angeles, 270 miles long, has the highest voltage that is considered feasible at present, 287,000 volts. At higher voltages the air around the conductor tends to "break down" and become conducting, allowing the electricity to leak off. Although such "corona" discharges may be minimized by using large conductors without sharp points, the highest practical limit for power lines in open air seems to be 250,000 to 300,000 volts. Three hundred to five hundred miles is about the longest distance over which it is now practicable to transmit energy from a single generating station without excessive losses. When higher line voltages are achieved, the practical transmission distance will increase.

Present-day Distribution Systems. Our present-day regional systems for the distribution of electric power imply vast extensions of the ideas we have outlined. Generating stations are now located strategically. Large generators driven by steam turbines are usually placed, if not near coal mines, then at least where there is an easy rail or water approach for coal or oil and preferably where there is a ready water supply for the engines. Hydroelectric plants are placed, of course, either near a natural source of water power such as the 167-ft "spillway" at Niagara Falls, or else where nature has provided a good location for large artificial dams which can store large quantities of water with usable potential energy, as at Boulder Dam on the Colorado River or the great Grand Coulee Dam on the Columbia River. Such factors as droughts and other seasonal variations in water flow enter into the planning of hydro-electric plants.

In large systems many generators, often at widely separated points, feed power into the same high-voltage transmission system. Because of fluctuating economic considerations, depending, among other things, upon seasonal water-level variations, many engineers



(*General Electric Company.*)

Fig. 239. Steel tower of 287,000-volt transmission line from Boulder Dam to Los Angeles.

believe that all electrical systems should have both steam and hydroelectric generating plants to supplement each other. High-voltage distribution-line networks often extend to many states, to cities, towns, and farms, and are sometimes called "grid" systems. There is much discussion now as to whether it would be desirable to have a nation-wide "grid" system, with generating stations all over the country feeding into one common high-voltage network, as is done on a smaller scale in England. Although it may not be entirely desirable to have a single universal network, this represents an interesting possibility.

Alternating-current Motors. Because alternating current is usually available from transmission lines, motors have been developed especially for operation by power from this source. Alternating-current motors are actually even simpler in construction than their direct-current relatives. In Fig. 240 a closed wire loop is shown between the poles of an electromagnet which has alternating current applied to it. Suppose that the indicated current is being induced by an *increase* of the magnetic field. Then if the magnetic field starts to decrease after the coil rotates 90 deg past the position

shown, the direction of the induced current will reverse, and the forces will be such that the rotation continues in the same sense. Once started, this process will continue indefinitely, with the number of revolutions per second in general equal to the alter-

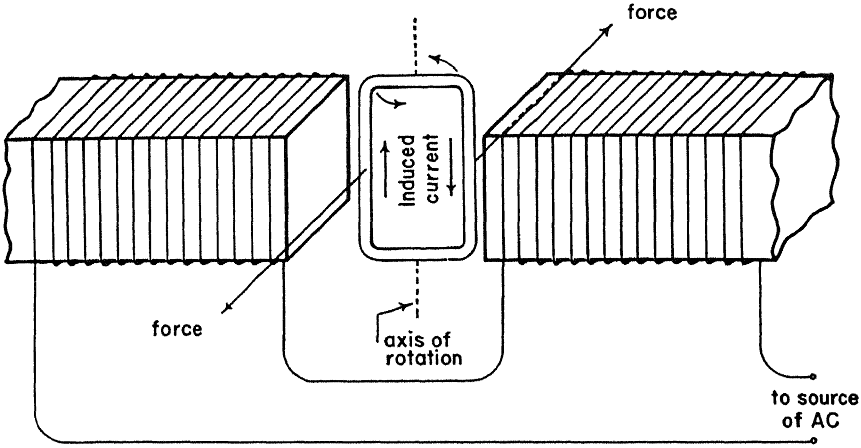


Fig. 240. Principle of AC induction motor.

nating-current frequency. Thus the main features by which this alternating-current motor differs from a direct-current motor are: the armature current is induced instead of being fed through brushes; the necessity for a commutator is eliminated because the direction of the induced armature current is reversed automatically twice each alternating-current cycle; the speed of rotation is controlled by the alternating-current frequency.

Another type of alternating-current motor is a bar of soft iron mounted on an axis in an alternating magnetic field (Fig. 241). If started with a rate of rotation equal to the alternating-current frequency, the bar will continue to rotate. This depends upon the fact that the induced magnetic poles in the soft iron "lag" behind the changing magnetic field, in such a manner that they are pulled forward after each rotation past the field poles.

The two types of alternating-current motor illustrated here are seen to be very similar in action when it is recalled that a single loop of wire with current in it is the simplest form of electromagnet. Then the operation of the first type of motor depends upon induced electromagnetism which changes with the alternating-current frequency, and the second upon ordinary induced magnetism which changes with the alternating-current frequency.

Electric clocks are simply alternating-current motors geared to hands for indicating the time. Most power companies keep their generators turning very accurately at the speed corresponding to their rated alternating-current frequency, so the speed of rotation

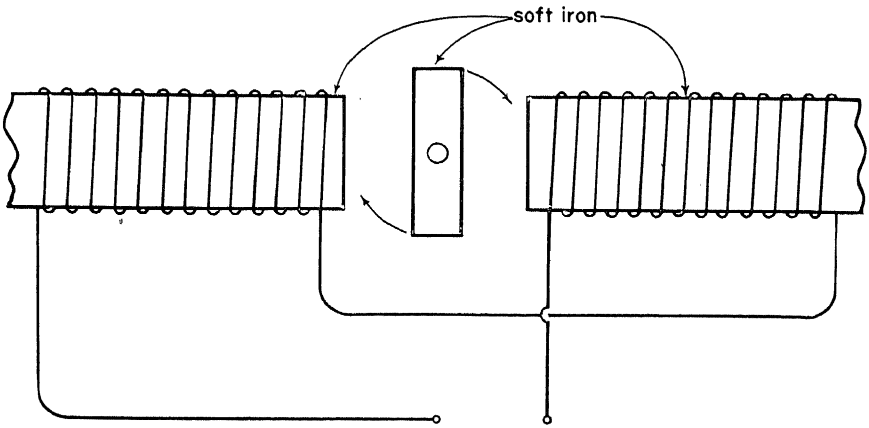


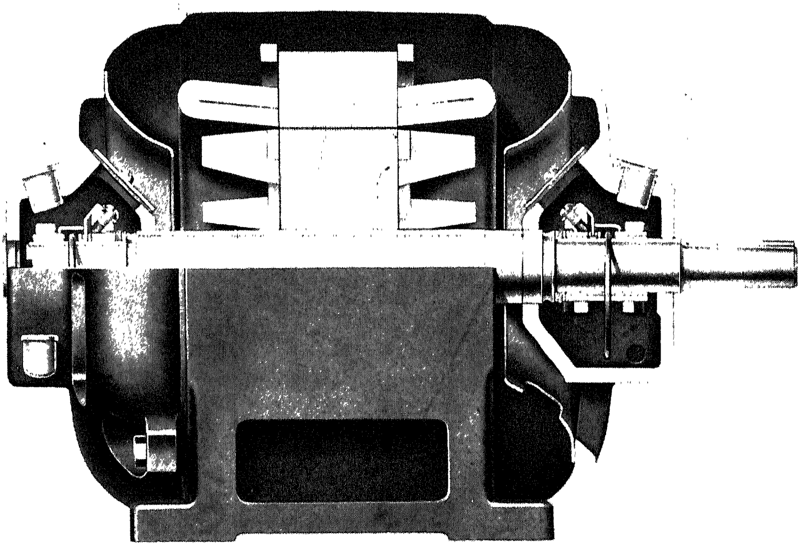
Fig. 241. Simple AC motor.

of the motor of a clock (which is determined by the alternating-current frequency alone) is dependably constant.

For purposes where variable speeds are required, such as supplying power to street railways, direct-current motors are ordinarily used because it is very difficult to change speed with alternating-current motors.

Three-phase Alternating Current. If you have looked closely at high-voltage transmission lines, you have seen that alternating-current transmission for large power use is generally accomplished by means of three associated wires. In these wires, the voltages have the same amplitude and alternate at the same frequency but are "out of step" with one another (that is, their "phases" are shifted) by one-third of a cycle. The end result is that between pairs of the wires there are possible three separate AC voltages which have their peaks at times one-third of a cycle apart. Discussion of this so-called "three-phase" alternating-current transmission is beyond the scope of this book. We can, however, call attention to its existence and to the fact that it has many advantages.

For example, a "three-phase" alternating-current motor need have only bars of copper arranged in a sort of "squirrel cage" to serve as its rotating armature, and the efficiency of such a motor is very high.

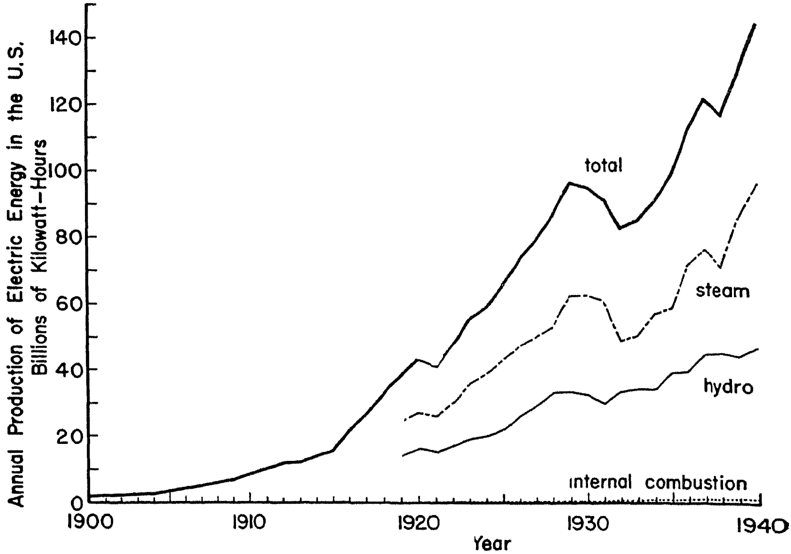


(*General Electric Company.*)

Fig. 242. Induction motor with squirrel-cage rotor.

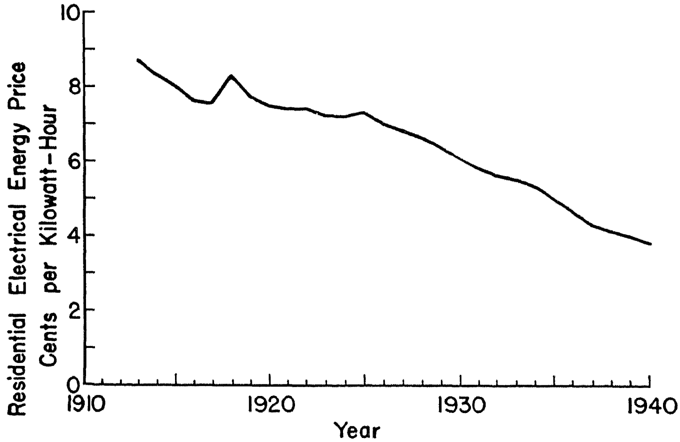
THE FUTURE OF ELECTRIC ENERGY

Trends. Consumption of electric power is now at the highest point in history, and existing power plants are inadequate to satisfy the demand. The use of electric energy has been increasing steadily, with only minor setbacks during depression years. Simultaneously, the cost per kilowatt-hour has been dropping. This decreasing cost comes from several influences. The efficiency of steam-driven plants has been more than doubled in the last 15 years. Losses in power transmission lines have been decreased greatly. And of course increased production ordinarily decreases the unit cost. Subsidized competition by municipally and federally owned plants such as those under the TVA and at Boulder Dam has naturally been a matter for considerable controversy, but, whether or not these plants function as "yardsticks," they have doubtless had their effect in reducing the cost of electric energy to consumer.



(*Data from The World Almanac, and the Federal Power Commission.*)

Fig. 243. There has been phenomenal growth in the annual production of electric energy in the United States. Although there have been more and more hydroelectric developments, steam generation continues to hold its lead.



(*Data from The Electrical Light and Power Industry in the United States, Edison Electric Institute.*)

Fig. 244. Average residential electrical-energy rates in the United States have declined almost steadily within the past few decades.

Intelligent Use of Energy. It has already been pointed out that, although our petroleum and natural gas supplies are great and the "visible" supply is so far keeping pace with increased use, these sources of energy can hardly last indefinitely. As long as the sun shines we shall have water power with us, but, while use of this energy supply can be expanded considerably, water power cannot provide for all our needs. Eventually we may utilize some other form of energy, such as that of ocean waves, light energy from the sun, or even atomic energy.

Even then, however, the distribution of energy for use in homes and industry may well be done by electricity. Our transmission lines may be huge vacuum or gas-filled concentric pipes underground, built to operate at much higher voltage than now, and they may cover the country as a vast network. High-voltage direct current may well be used, because alternating current rises to a "peak" voltage which is higher than the equivalent direct-current value, so the direct current is less likely to produce a breakdown. Indeed, methods are now being developed to step up and down direct current.

We may be sure that, whatever sources of energy may be used in the future, the amount available to do the world's work will increase steadily. Rightly used, this energy offers immense possibilities for improving life and living. A tremendous responsibility rests on both scientist and layman to see that these opportunities are realized.

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SUMMARY

Electrically a simple direct-current motor is similar to a galvanometer except that the ***armature*** rotates continuously by means of a ***commutator*** and ***brushes*** which change the direction of current in the armature as each ***field*** pole is passed. An armature

usually is several coils wound on iron, each connected to a pair of commutator segments. In ***shunt*** motors, ***field coils*** and armature are in parallel, and in ***series*** motors they are in series.

For electric motors, the efficiency is the ratio of output energy to input energy, also the ratio of output power to input power. The input power = (line voltage) × (current). The output power = (force) × (distance per second through which the force acts). As the ***load*** on a motor is increased, the efficiency increases from zero to a maximum and then drops.

In 1831 Faraday discovered ***electromagnetic induction.*** When a magnetic field and properly oriented conductor in it move with respect to one another, voltage is induced in the conductor.

In a coil rotating in a properly oriented magnetic field, there is induced a voltage which changes direction once each revolution. This arrangement is the simplest ***alternating-current*** (AC) ***generator.*** A commutator can take from the coil voltage which is always in the same direction; this makes a ***direct-current*** (DC) generator, and it is just like a direct-current motor. The electric energy produced by a generator is always less than the mechanical energy supplied to it.

Alternating current in a coil continually induces voltage in a near-by coil. Two coils on the same iron core constitute a ***transformer.*** An AC voltage applied to one coil, the ***primary,*** produces an AC voltage in the other coil, the ***secondary.*** The ratio of the secondary voltage to the primary voltage equals the ratio of the number of turns in the secondary to that in the primary. There is practically no current in the primary of a good transformer unless there is current in the secondary. The secondary power is always less than the primary power, although efficiencies range to 98 per cent. A ***step-down*** transformer gives a secondary voltage that is smaller than the primary voltage, a ***step-up*** transformer the reverse.

If the resistance of a transmission line is R and the current in it is I, the voltage drop in its length is RI and the power loss is RI^2. For a given power, VI, these factors can be reduced by making the voltage, V, large and I small. In most power systems generators supply low voltage which is "stepped up" for transmission and "stepped down" again for consumption. The currents in the parts of the system are almost inversely proportional to the voltages. High voltage makes possible long-distance transmission.

A simple alternating-current motor is a closed coil, a copper squirrel cage, or even a bar of soft iron properly mounted in a magnetic field produced by alternating current. The armature rotates at a speed determined by the alternating-current frequency.

Use of electric energy is increasing, and its cost is decreasing. Even if fuel supplies become exhausted, hydroelectric power will be available, but additional energy sources will almost certainly be needed.

QUESTIONS

1. Describe Faraday's discovery in 1831 about voltage induced in a wire moved through a magnetic field.
2. How does a motor differ in principle from a galvanometer?
3. What are the essential parts of a direct-current motor?
4. What are the essential parts of a generator?
5. What determines how much mechanical energy must be supplied to rotate the armature of a generator?
6. Why can a direct-current motor serve as a generator if its armature is rotated?
7. What is the difference between alternating-current and direct-current generators?
8. What is meant by 60-cycle AC?
9. Why must the peak value of 120-volt AC be larger than 120 volts?
10. Why is high voltage necessary for a long-distance transmission line?
11. When the 287,000-volt transmission line from Boulder Dam to Los Angeles carries 1,000 amp, what is the greatest possible current being drawn in Los Angeles at 120 volts? How many 100-watt lamps could be supplied by the power involved?
12. Describe step-up and step-down transformers.
13. Why can't we use transformers on direct current?
14. Why do large-scale energy projects, such as the TVA development or the Boulder Dam project, always involve electric energy?
15. How cheap can power be?
16. Why does electric energy appear to be so fundamental? Is there a real distinction between electric energy and the other forms of energy?
17. Is it possible to "store" energy? On a small scale? On a large scale? For a short time? For a long time?
18. Describe a simple alternating-current motor and explain its operation.

CHAPTER XII

MOTION WITHIN MATTER

MOLECULES AND PRESSURE

One of the great intellectual triumphs of the last century was the development of the atomic theory of matter. Along with the increased knowledge of the structure of matter, of the effects of temperature and energy changes upon gases, liquids, and solids, came the evolution of steam, gasoline, and Diesel engines. We should not overlook the practical importance of the influence of the theory of molecular motion—the ***kinetic theory***—on the development of these substitutes for human labor.

The World of Molecules. We have already informed ourselves about the growth of many ideas concerning elements and compounds, atoms and molecules. According to these ideas, any piece of ordinary matter, whether solid, liquid, or gaseous, would, *if* it could be magnified sufficiently, appear as a myriad of individual particles called molecules. Each of these molecules might be found to consist of a single atom, but more probably it would be a closely linked group of two or more of the 88 natural types of atom.

The idea that the molecules of all materials must be in ***rapid and continual*** motion was adopted gradually by men who studied the behavior of gases, liquids, and solids at various temperatures and pressures. After John Dalton's suggestion that gases must consist of individual particles, James Joule and others concluded that the ***pressure*** exerted by gases on the walls of containers which hold them must result from continual motion of the gas molecules. The beating and bouncing of the gas molecules against the walls must be the cause of this pressure. We shall see that this idea of molecules in motion accounts for many varied phenomena which would otherwise be difficult to explain.

It is apparent that the rain of many individual molecules on a surface could produce what seems like a steady pressure. Suppose,

for example, that lead shot are allowed to fall so that they bounce off a conical surface placed on top of a spring balance (Fig. 245). If the shot fall in sufficient numbers in a continued stream the spring balance will show a more or less steady force.

The picture of a kinetic gas, that is, one composed of sub-microscopic molecules that are in rapid and chaotic motion, bumping into each other and the walls or other objects around them, naturally seemed fantastic at first, but gradually it has been substantiated by many sorts of experiments.

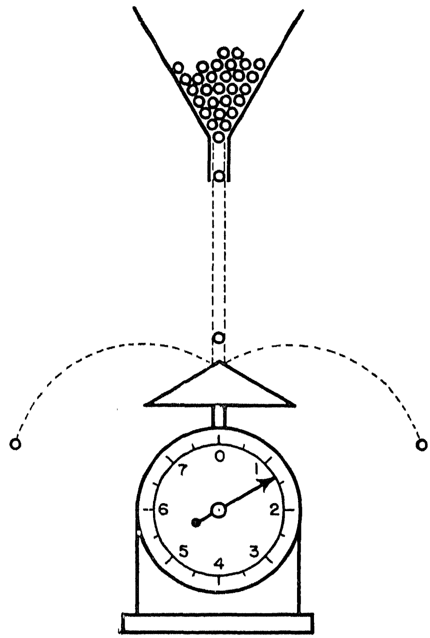
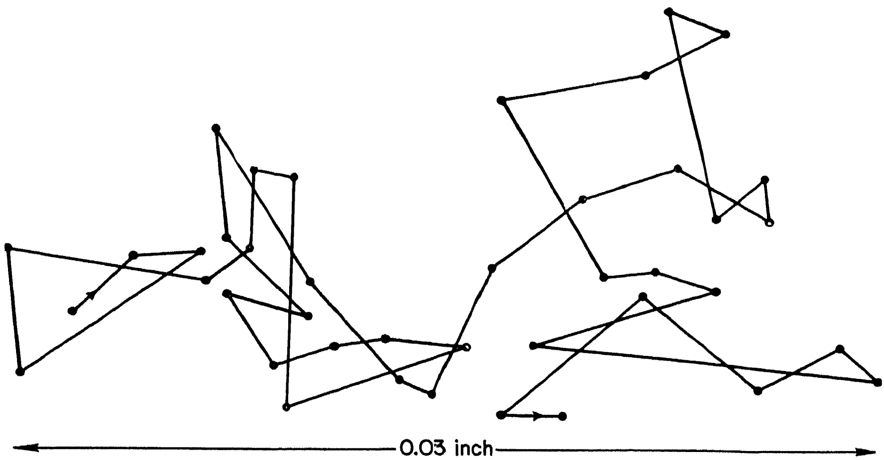


Fig. 245. A rapid succession of impulses from falling shot can give the effect of a rather steady force.

The Brownian Motion. In 1827 the English botanist, Robert Brown, noticed in his microscope a strange jerky quivering motion of tiny pollen grains and spores which were suspended in water. Subsequently any sufficiently fine particles, such as those of smoke or dust, were found to have this same sort of motion when suspended in a liquid or gas. The path of a single particle would be very irregular, as in Fig. 246.

For many years this peculiar motion remained unexplained. When the concepts of the kinetic theory developed, it was realized that this jerky motion was exactly what should be expected. The diameter of ordinary gas molecules, such as O_2 and N_2 which largely make up our air, is about two to four hundred-millionths of a centimeter (2 to 4×10^{-8} cm). Molecules are so small that they are ***completely invisible,*** because even the best optical microscope cannot form an image of an object much smaller than about one ten-thousandth (10^{-4}) centimeter. Tiny smoke particles of, say, one-thousandth (10^{-3}) centimeter diameter can be seen with a microscope, but are still so small that the molecular impacts at any instant will not completely annul each other. For example, in one tiny fraction of a second, perhaps 1,000,000 million molecules may

hit the smoke particle on one side, and only 999,998 million hit it on the opposite side. Later, in a similar interval, it may be hit by 999,999 million molecules on the first side and 1,000,002 million on the other. The result is that the visible smoke particle is buffeted



(After Jean Perrin.)

Fig. 246. Brownian motion of a tiny solid particle in water. Positions at 1-sec intervals of a particle $\frac{2}{1,000,000}$ in. diameter.

by the invisible air molecules first in one direction, then in another, and so has the characteristic jerky motion.

Once seen, the Brownian motion is convincing evidence of the motion of molecules, even though we see the *effects* of the high-speed molecules and *not* the molecules themselves. Careful measurements show that the amount of the observed motion is precisely what one should expect from the relative sizes of the particle and molecules and the molecular speeds. Ordinary objects, of course, are so large and so heavy that inequalities in molecular bombardment have no appreciable effect on them, so no Brownian motion is observed.

Gases and Pressure. The air through which we move seems almost like nothing at all, yet it certainly exerts large forces. If we tie a thin rubber sheet over the opening of a vessel, the sheet lies flat because the air pressure is the same on both sides. If, however, we exhaust the air from the vessel by means of a pump, the air outside

forces the rubber to stretch and press tightly against the inside of the vessel; it even may rupture the sheet.

The concept of pressure is useful in the consideration of gases. And it is very important to understand the distinction between *pressure* and *force*. ***Pressure is force per unit area***

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{lb/in}^2 \text{ or newtons/meter}^2$$

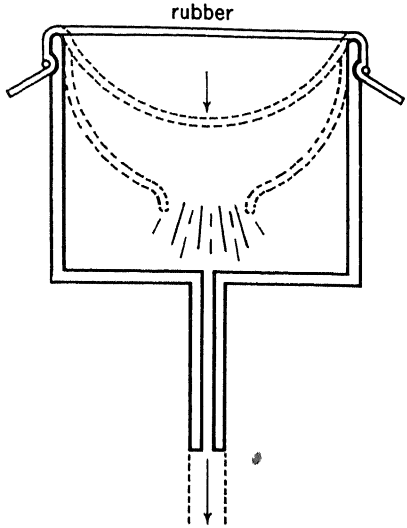


Fig. 247. Evidence of atmospheric pressure.

The pressure at the bottom of a column of a gas or liquid, say water, of a given height will be the same regardless of the area or shape of the particular tube enclosing it. For example, the water in each of the containers of Fig. 248 exerts the same pressure at the bottom. If this were not the case, water would flow from the containers with high pressure to those of low pressure until the pressures at the bottom were equalized.

In a cylinder, the total weight of the water is proportional to

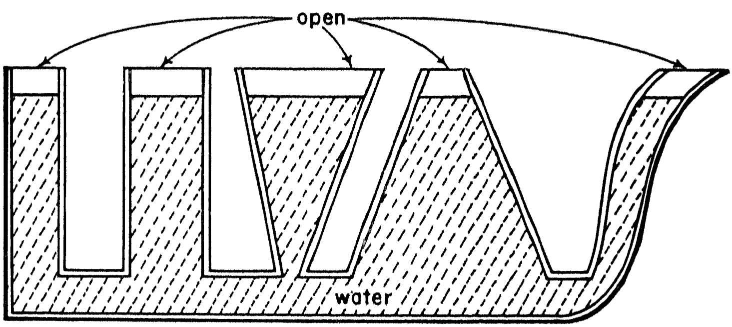


Fig. 248. Water stands at the same level in each vessel regardless of the various forms because the pressure at the base of each vessel depends only upon the height of the liquid.

the cross-sectional area, and when divided by the area the result (pressure) is independent of the diameter of the tube. In fact, a

little reflection will show that the pressure due to a column of any uniform fluid of height h and density D is just

$$\text{Pressure} = \text{height} \times \text{density} \times g$$

or

$$\text{Pressure} = hDg$$

If we hang a weight on a piston which fits smoothly inside of a cylinder, and then exhaust the air from the cylinder, the excess upward force of the air on the movable piston will lift surprisingly heavy weights. The air pressure on a piston with a diameter of only 4 in., and, therefore, with an area of $\pi \times 2^2$ or about 12.5 in², will lift 185 lb! Recalling that

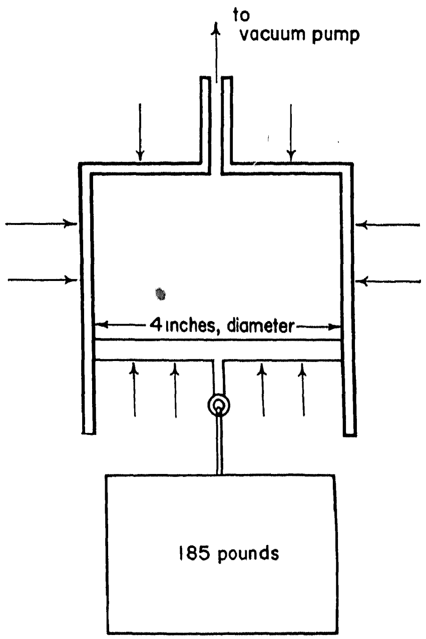


Fig. 249. Atmospheric pressure is nearly 15 lb/in².

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

a little simple arithmetic shows that the pressure of air under normal conditions must be nearly 15 lb/in².

Normally we don't feel much effect from this atmospheric pressure of about 15 lb/in², for the same pressure is exerted through us from all sides so there is complete balance. In our bodies, for example, the outward pressure of the air in our lungs and through the blood is almost counterbalanced by the pressure of the air on the outside. Breathing is of course made possible by air pressure, for when respiratory muscles expand the chest cavity, air rushes in to fill the lungs until a constant pressure is attained.

Without doubt, you have seen fluid pressure used at filling stations and garages to lift cars for greasing and inspection. If air, say under a pressure of 100 lb/in² above normal atmospheric pressure, is allowed to press against a piston of 12 in. diameter, the total force will be

$$\begin{aligned} \text{Force} &= \text{pressure} \times \text{area} \\ &= 100 \text{ lb/in}^2 \times (\pi \times 6^2) \text{ in}^2 \\ &= 11{,}300 \text{ lb} \end{aligned}$$

This, of course, is ample to lift any car with great ease, for few weigh more than 5,000 lb.

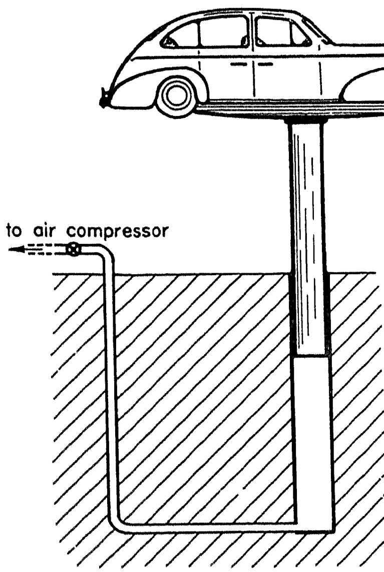


Fig. 250. Pressure lift commonly used in service stations for chassis inspection and lubrication.

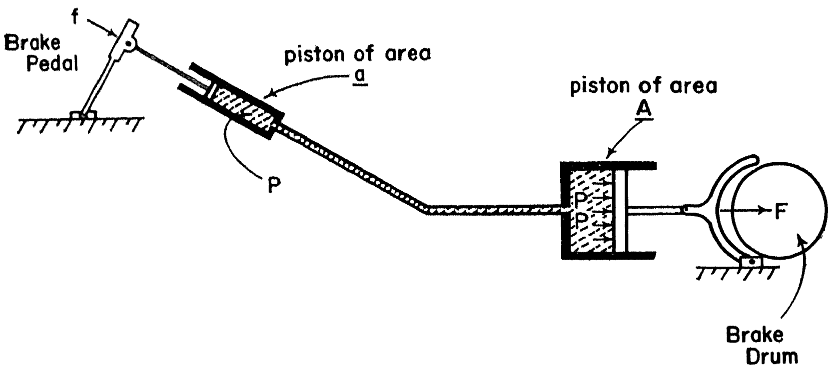


Fig. 251. Hydraulic-brake system.

The "hydraulic" brakes on your car depend upon a similar arrangement for transmitting pressure. Usually a fluid such as oil is used in automobile brakes, but compressed air is often sub-

stituted in heavy trucks and railroad cars. The pressure exerted on an enclosed gas or liquid is transmitted equally throughout the material, so a comparatively small force f (Fig. 251), applied by means of the brake pedal onto a piston of small area a, will produce a large pressure P, since

$$P = \frac{\text{force}}{\text{area}} = \frac{f}{a}$$

This pressure on the enclosed fluid in the brake system can in turn be made to exert a large force F on a large piston of area A which operates the brake, because

$$F = P \times A = f\frac{A}{a}$$

The Torricellian Barometer. The Italian physicist Torricelli (1608–1647), who had served as Galileo's assistant, cleared up many early misconceptions about pressure and the nature of a vacuum. To him we owe the first *barometer,* an instrument for measuring atmospheric pressure. A glass tube about one meter in length and closed at one end was filled with mercury and inverted with the open end in a cup of mercury. Regardless of the shape or size of the tube, the mercury always fell from the top of the tube until its height above the mercury level in the cup was about 76 cm (30 in.). Torricelli reasoned that above the mercury was simply a space practically devoid of matter. According to this view, there could not possibly be anything to the then-popular idea that a vacuum "pulled" the mercury up. Rather he concluded correctly that his barometer was just like a balance, but a *pressure balance* instead of a force balance. The air from the surface up to the top of the atmosphere was exerting a pressure on the open surface of the mercury in the cup, and this pressure was balanced exactly by the opposing pressure on the

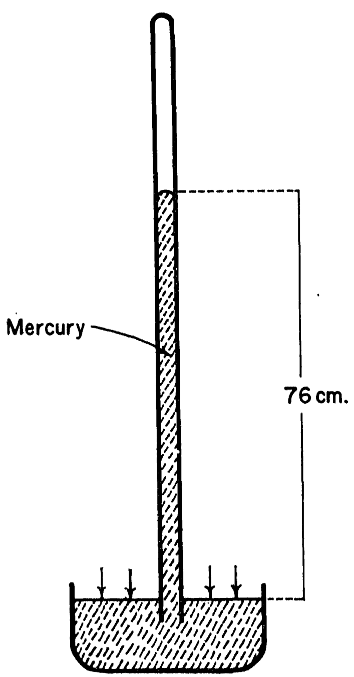
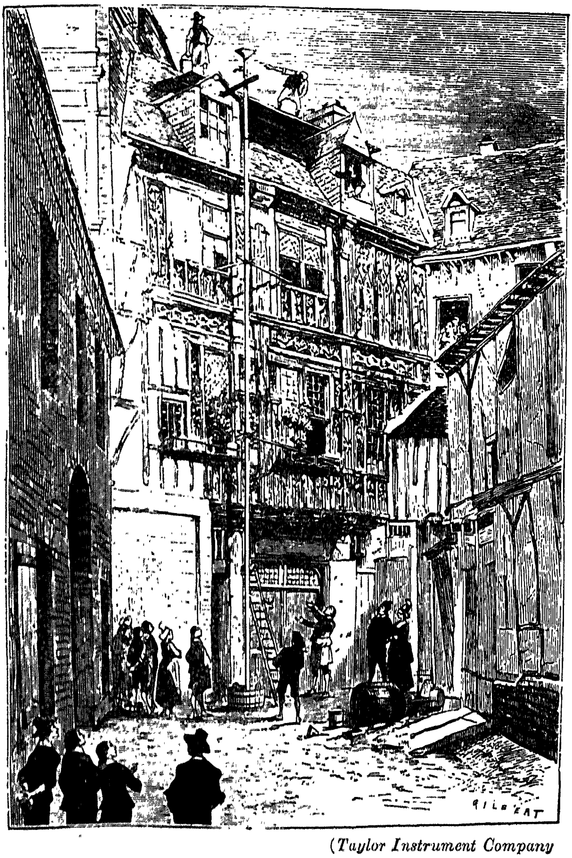


Fig. 252. Mercury barometer.

same mercury surface due to the 76 cm column of mercury above it.

Pascal (1623–1662), a French contemporary of Torricelli, is said to have astonished his neighbors by building a tube over 45 ft



(*Taylor Instrument Company*

Fig. 253. Water barometer of Pascal and Petit at Rouen, 1646.

long on the side of his house. He showed that water behaves just like mercury, but that the atmospheric pressure balances a column of water about 34 ft (10.3 meters) high. This is about 13.6 times the height of a mercury column in a barometer, and since mercury is 13.6 times as dense as water, equal pressures or weights per unit area would be exerted by the mercury and water columns. Thus they are equally effective in balancing the atmospheric pressure.

Often, rather than bother to express pressures in terms of pounds per square inch or newtons per square meter, we simply

give a pressure as the height in centimeters of the mercury column that will produce that pressure. Thus, pressure is commonly given in centimeters of mercury (cm Hg).[1]

Pascal showed that the height of a mercury column in a barom-

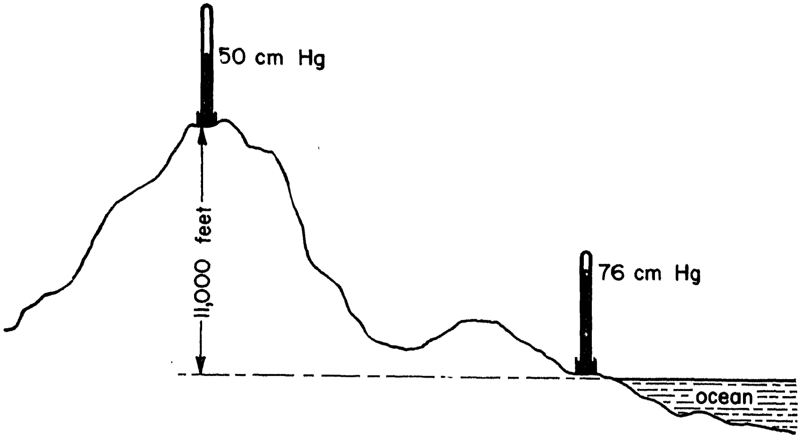


Fig. 254. **Pascal discovered that barometric pressure decreases as altitude increases.**

eter decreases when the barometer is carried to the top of a mountain. This is because the amount of air above it is decreased. He also observed strange variations of the barometric height which seemed to depend on the weather. This was perhaps the beginning of the science that is known today as meteorology.

Other Kinds of Barometers. Mercury barometers should be mounted stably and are rather inconvenient to read, so another more portable type of barometer, the so-called *aneroid* barometer, is often used. A tight flexible metal bellows has a fixed amount of air enclosed in it. When the outside air pressure increases, the bellows is compressed; similarly, when the air pressure outside decreases, the bellows is extended. A pointer attached as in Fig. 255 can be forced by the bellows to move up and down on a scale and so show atmospheric pressure variations.

Airplanes generally use barometers like this for altimeters, that is, to indicate their height above ground. Since the atmospheric pressure decreases with altitude, the barometer scale can be

[1] The Weather Bureau formerly used inches of mercury to express barometric pressure, but recently, by international agreement, the millibar has been chosen as the standard unit of barometric pressure. 1 millibar (1/1,000 of a bar) is equal to 100 newtons/meter^2. Normal atmospheric pressure on this scale is about 1,013 millibars.

calibrated to read altitude. The readings, however, depend also on weather conditions, so a pilot would have difficulty in distinguishing between the effects of changing weather and changing altitude. Furthermore, in a mountainous region a knowledge of the height

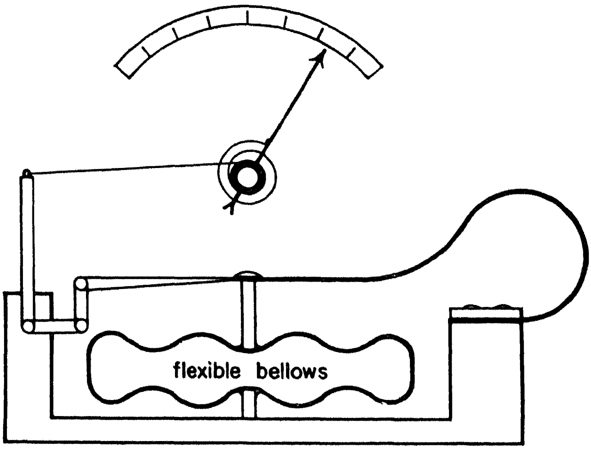


Fig. 255. Aneroid barometer.

above sea level is often of little value in determining the height above the ground. The inability to tell height above the ground accurately has been a contributing factor to many airplane accidents, particularly when "blind flying" was necessary in bad weather or at night. Recently there have been developed more accurate altimeters depending on radio techniques.

Measuring Pressure. In order to make possible studies of fluids, that is, of gases or liquids, scientists and engineers need convenient methods of measuring pressure. Some knowledge of these methods is necessary if we are to appreciate the progress in almost any field of science.

Manometers. One of the simplest and most accurate devices for pressure measurement is the manometer. In one common form, a U-shaped tube open at one end is partially filled with mercury (Hg), or perhaps some other liquid, and connected to the container holding the fluid whose pressure is to be measured. The manometer is just like a balance. The gas in the container (Fig. 256) exerts pressure on the mercury surface facing it, and the air outside exerts a pressure, which is usually about 76 cm Hg at sea level, on the mercury in the open tube. If the pressure of the gas inside the

container is greater than the atmospheric pressure, as in the figure, the mercury is pushed down on the side next to the vessel and up in the open tube until the excess of mercury on the open side just counterbalances the pressure difference. If h is the difference in

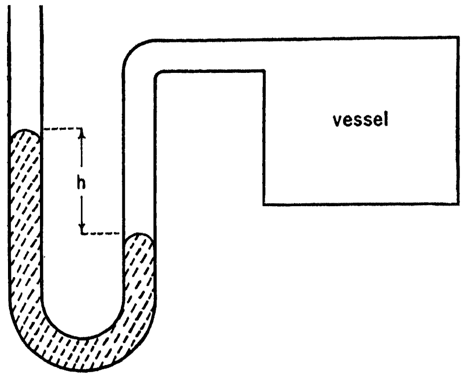


Fig. 256. An open mercury manometer.

height of the mercury on the two sides, the actual pressure in the container is then h cm Hg greater than atmospheric pressure. The true pressure in the container, in *centimeters of mercury,* is then h cm plus the barometric pressure. If h is 10.1 cm Hg and atmospheric pressure as read at the time on a barometer is 75.1 cm Hg, the true pressure of the gas is 85.2 cm Hg.

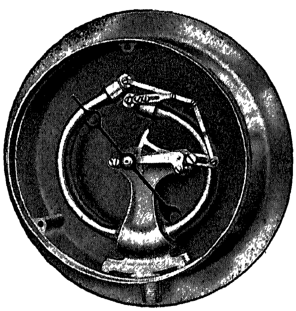


Fig. 257. Mechanism of Crosby pressure gage, double-tube type.

If, on the other hand, the pressure of the enclosed gas is less than atmospheric pressure, the mercury is higher on the side next to the vessel. The difference in height of the two mercury columns must then be *subtracted* from the barometric pressure to give the gas pressure. If there were a nearly perfect vacuum in the container, the difference in height of the two mercury columns would be just the barometric pressure.

Bourdon-type Pressure Gage. Although accurate, mercury manometers require a rigid mounting and are somewhat fragile, so another type of pressure-measuring device is often used where ruggedness and portability are important. The so-called Bourdon gage operates somewhat like the coiled paper snakes sold at county fairs, which unroll when blown. In such a gage, increased pressure in a thin coiled metal tube makes it

tend to unwind and move a pointer over a dial calibrated to read in pounds per square inch, centimeters of mercury or whatever other pressure units are desired.

Gage Pressure and Total Pressure. When a gage such as

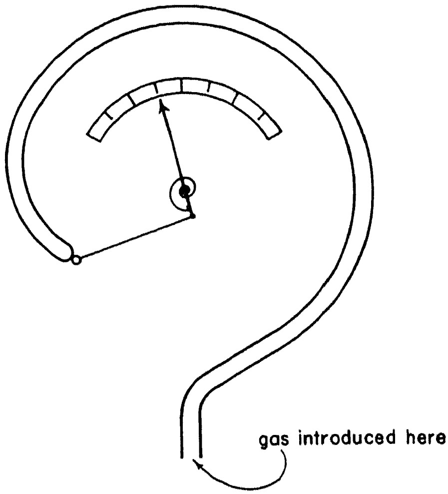


Fig. 258. Principle of Bourdon gage.

the Bourdon type is used to measure pressure, for example, of the air in a tire, care must be taken if the ***total pressure*** is desired. Most such gages are arranged so that the dial reads zero when the gage is open to the atmosphere. But we know that the atmospheric pressure of about 15 lb/in^2 (or 76 cm Hg) is acting even then. Consequently 15 lb/in^2 (or 76 cm Hg) must be added to the ***gage pressure*** reading to obtain the ***actual pressure*** in the tire. If a gage reads zero before it is connected to the tire, and 30 lb/in^2 afterward, this latter reading is the gage pressure, and the total pressure is about 45 lb/in^2.

THE GAS LAWS

Boyle's Law. Robert Boyle performed some of the first good experiments showing the relation between the pressure and the volume of an enclosed mass of gas. To illustrate them, let us suppose that a fixed mass of some gas is trapped in the closed end of the tube shown in Fig. 259. If the mercury surfaces on the two sides are initially at the same level, the pressure of the gas must be just atmospheric pressure ("one atmosphere"). If we pour mercury into the open tube, we find that in order to compress the gas to

one-half its initial volume, enough mercury must be added so that the difference in height of the two columns is about 76 cm, or so that the actual gas pressure is about two atmospheres. Boyle's conclusion is simple. In order to halve the volume of some enclosed

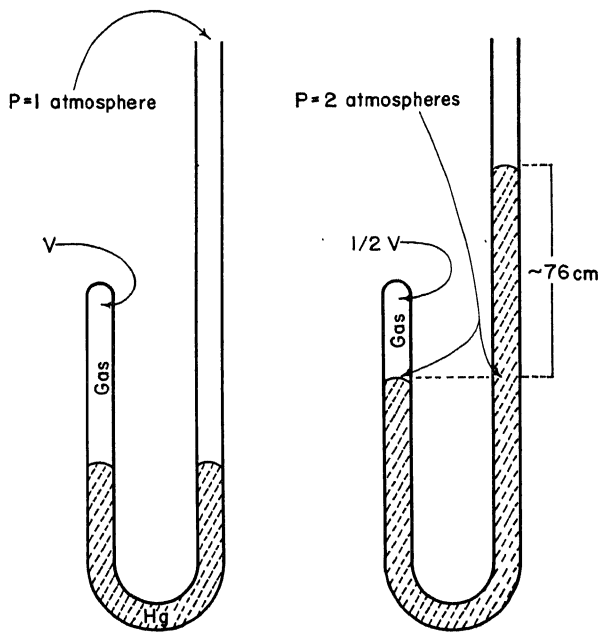


Fig. 259. Boyle's gas law.

gas by changing the pressure, the pressure on the gas must be doubled, or, stated more generally, ***the pressure of a given mass of gas is inversely proportional to its volume if the temperature remains unchanged.*** We can say that if P_1 and V_1 are the initial pressure and volume, and P_2 and V_2 the final pressure and volume, then

$$P_1V_1 = P_2V_2$$
$$= \text{constant, for a fixed mass of gas at a fixed temperature.}$$

(Don't forget that the pressure must be the ***total pressure*** of the gas, not the gage pressure.)

Charles's Law. Charles and the French physicist Gay-Lussac independently made the first investigations of the way in which the pressure and volume of gas depends upon its temperature. We can best understand their conclusion by imagining that we

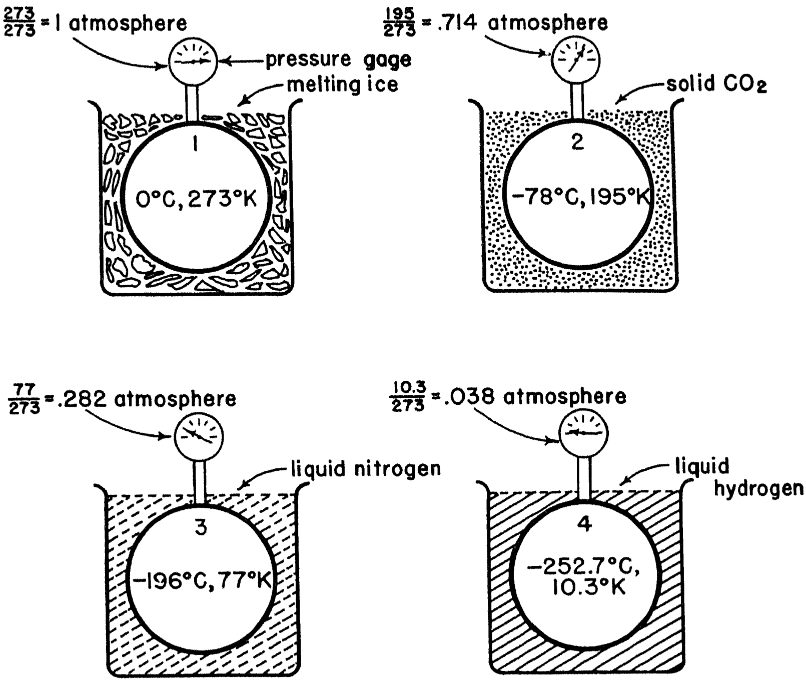


Fig. 260. Charles's gas law—the pressure of the helium in the vessel is directly proportional to the absolute temperature.

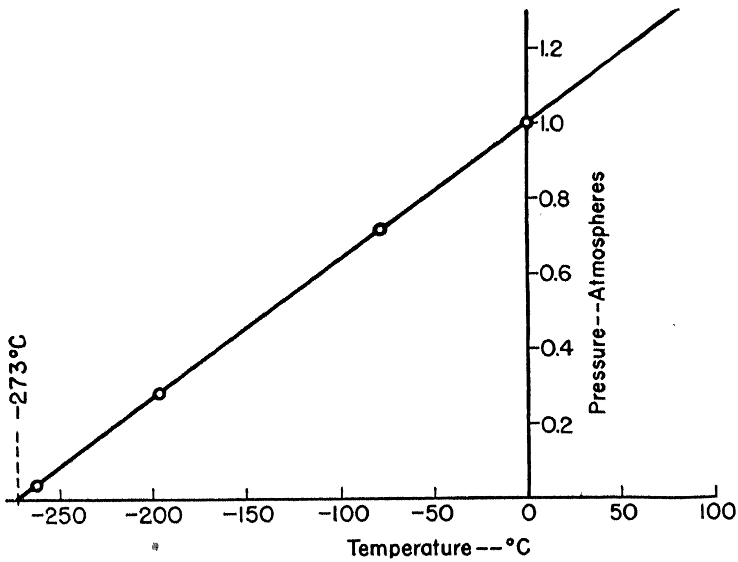


Fig. 261. Variation of pressure with centigrade temperature of some helium at a constant volume.

perform some experiments. Suppose that we enclose a certain mass of gas in a container which has a pressure gage or a manometer attached. Then let us see what happens when the container is subjected to various temperatures. Air would serve in the container if the temperature is kept above the point at which air becomes a liquid, but helium, as we have seen, remains gaseous at a much lower temperature.

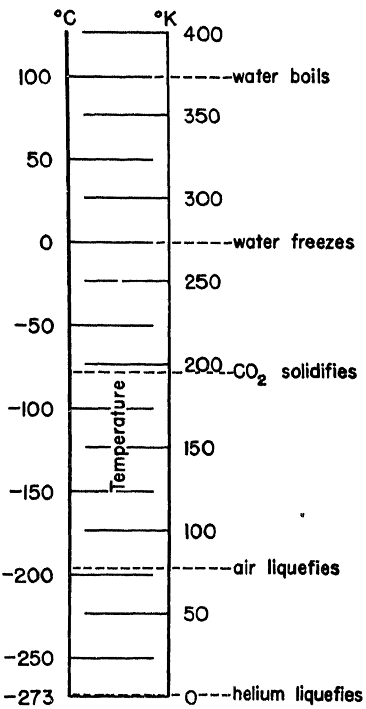


Fig. 262. Comparison of centigrade and absolute temperature scales. The processes refer to normal atmospheric pressure.

We find that when the temperature is lowered the pressure decreases steadily as shown by the gauge readings in Fig. 260. When the pressures are plotted against temperature the result is surprisingly simple, for the curve is a straight line. The pressure readings decrease with decreasing temperature, and extension of the straight line shows that if the gas did not liquefy the pressure would become zero at −273°C (more accurately −273.18°C), which we call the absolute zero of temperature.

This relation between pressure and temperature can be expressed very conveniently if we use a temperature scale just like the centigrade scale except that its zero is absolute zero. This temperature scale is called the ***absolute*** or, often, in honor of Lord Kelvin who clarified many concepts of kinetic theory, the ***kelvin*** scale. Then, the relation between temperature Kelvin (°K), and temperature on the ordinary centigrade scale (°C) is

$$(\text{Temperature } °\text{K}) = (\text{temperature } °\text{C}) + 273$$

Many descriptions of the behavior of matter become simplified if we change to this absolute temperature scale. If more had been known about molecules and the way they act, a more rational temperature scale might have been adopted originally. Early temperature scales, however, were largely matters of convenience at the moment.

The results of the experiment just described can now be stated simply:

The pressure exerted by a given mass of gas is directly proportional to the absolute temperature if the volume is constant.

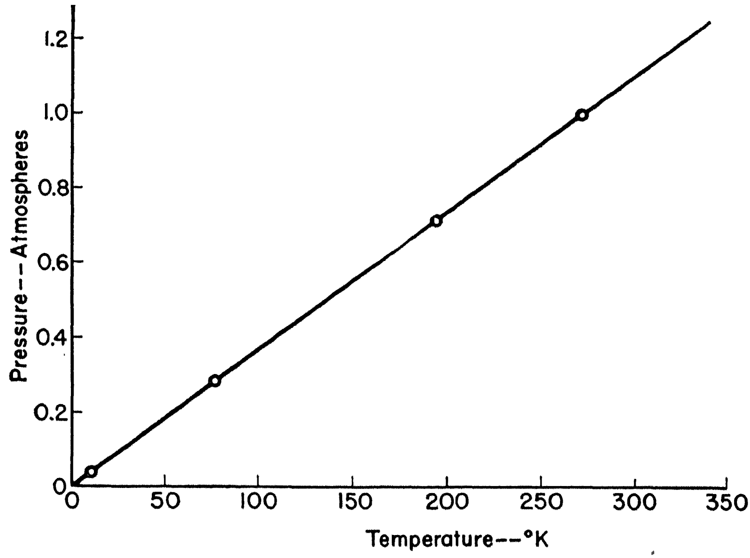


Fig. 263. Variation of pressure with absolute temperature of some helium at a constant volume.

This is Charles's law. Of course, this description could not apply to any matter in the region of absolute zero temperature because all real gases liquefy before that point is reached. This is one of the reasons that Charles's law is said to apply strictly to "ideal" gases only. The relation between the pressures P_1 and P_2 at two different absolute temperatures T_1 and T_2 (volume being constant) can now be expressed as a simple proportion

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}, \text{ for a fixed mass of gas at a fixed volume}$$

Before starting on a motor trip on a hot summer day you may have filled your tires to 30 lb/in^2 gage pressure or 45 lb/in^2 actual pressure in a comparatively cool garage where the temperature is perhaps 27°C or 300°K. In driving at high speeds on hot pavements the tire temperature may rise to as much as 97°C or 370°K, which is hot enough to blister a finger. The tire casing does not allow the volume to change much, so the pressure rises and the car seems to

"ride much harder." Since

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

we can say

$$\frac{45 \text{ lb/in}^2}{(\text{pressure when hot})} = \frac{300°}{370°}$$

or

$$(\text{Pressure when hot}) = \frac{370°}{300°} \times 45 \text{ lb/in}^2 = 55.5 \text{ lb/in}^2$$

A tire gage would read 55.5 − 15.0 or 40.5 lb/in² instead of the 30 lb/in² at the start of the trip. No wonder the car seems to ride harder!

Volume and Temperature of a Gas. Another interesting experiment is to see what happens to the volume of some gas when the temperature is changed while the pressure is maintained constant. This is a little more difficult to perform accurately than are the experiments leading to Boyle's law and Charles's law. But when it is done it gives just the relation that the other gas laws would lead us to expect: ***the volume of a given mass of gas is directly proportional to the absolute temperature if the pressure does not change.*** The volume would become zero at absolute zero, except that molecules, of course, do have a definite volume. When the molecules, which were flying about freely as a gas, have their speeds lowered so much that their natural attraction for each other gets the upper hand, they stick together or "condense" to form a liquid.

When a gas liquefies its volume drops suddenly to a value beyond which it cannot decrease much further. Consequently, the statement of the third gas law applies only for temperatures higher than the temperature of liquefaction of the gas (which depends somewhat on the pressure). This law can also be expressed in the simple form

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}, \text{ for a fixed mass of gas at a fixed pressure}$$

The General Gas Law. In most cases which physicists, chemists, and engineers have to consider, the pressure, volume, and tempera-

ture all can vary. Then a sort of combination of the three gas laws must apply. This general gas law states simply that the product of pressure and volume is proportional to the absolute temperature for a fixed mass of gas; or, if the mass M of the gas is subject to

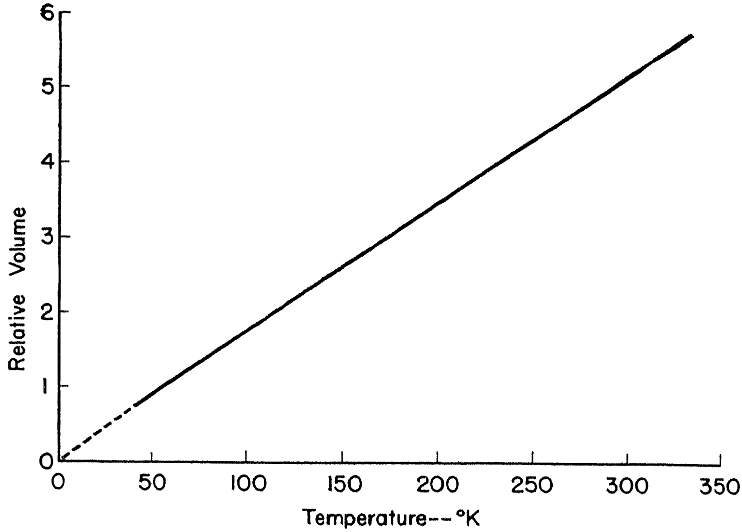


Fig. 264. At constant pressure, the volume of a given mass of gas is proportional to the absolute temperature. This holds only when the temperature is well above the condensation point.

change

$$PV = kMT$$

where k is a constant for any single kind of gas; or this relation may also be expressed

$$\frac{P_1V_1}{P_2V_2} = \frac{M_1T_1}{M_2T_2}$$

We may recall that, according to Avogadro, equal volumes of gases at a standard temperature and pressure (usually NTP[1]) contain equal numbers of molecules (see page 186). In other words, the masses of gas in equal volumes are proportional to the molecular weights of the gases. Now, we can find one volume so that at NTP[1] it contains a mass of gas in grams that just equals the molecular weight of the gas, that is, this standard volume which turns

[1] 0°C and 76 cm Hg.

out to be 0.0224 meter^3 or 22.4 ***liters,*** contains one ***gram-molecular weight***[1] of gas.

Now if, in the equation $PV = kMT$, M is taken as one gram-molecular weight (M_0) of the gas, kM or kM_0 is a ***constant for all gases.*** This can be seen easily, because, as we have just learned, one gram-molecular weight of ***any*** gas has a volume of 0.0224 meters^3 at 76 cm Hg and 0°C (273°K); so $PV = kM_0T$ gives

$$kM_0 = \frac{PV}{T} = \frac{(76 \text{ cm Hg}) \times (0.0224 \text{ meters}^3)}{273°\text{K}} = K, \text{ a constant}$$

Thus, if we always choose one gram-molecular weight of gas with which to work, the general gas law takes a form which chemists find very useful. It is

$$PV = KT$$

where K is the same constant for all gases. As long as the mass and kind of gas used is the same it is obvious that this equation gives the second form of the general gas law

$$\frac{P_1V_1}{P_2V_2} = \frac{T_1}{T_2}$$

If we add the condition that T be constant, then $T_1 = T_2$, and the last expression becomes $P_1V_1 = P_2V_2$, which is just the algebraic statement of Boyle's law. Similarly, the other two gas laws come out of the general law when V and P, respectively, are made constant.

The Kinetic Theory Explains the Gas Laws. James Joule in 1847 explained how the behavior of gases can follow directly from the properties of molecules in motion. In so doing he clarified the idea of absolute temperature, giving an interpretation which is used to this day.

Joule's reasoning may be stated thus: Myriads of gas molecules bouncing about within a closed box produce a pressure on the walls of the box as the result of their impacts. If the molecules behave like small elastic spheres, each one that approaches a wall with a velocity s bounces off with the same velocity in the opposite direc-

[1] One gram-molecular weight of hydrogen gas, H_2 (atomic weight 1, molecular weight 2), would be 2 grams, and similarly for oxygen gas, O_2 (atomic weight 16, molecular weight 32), it would be 32 grams. Each would occupy 22.4 liters at NTP.

tion, that is, with a velocity $-s$. The change of velocity is, thus, $2s$. Because a force is required to change the velocity of any object, the wall must exert a force on the rebounding molecule; and the molecule exerts an equal but oppositely directed force on the wall. Newton's laws of motion (page 58) show how to calculate the force and, consequently, the pressure exerted on the wall by all the molecules rebounding from the wall. Such a calculation gives the pressure P in terms of the volume V of the box, the number of gas molecules N, and the average kinetic energy of one of the molecules ($\frac{1}{2}mS^2$). The result is[1]

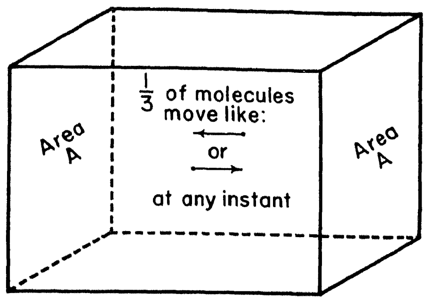


Fig. 265. Molecules moving across the box exert force on the ends.

$$P = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}mS^2\right)$$

[1] The way in which Joule reached his conclusion is really quite simple. Suppose that N molecules of the gas are in a rectangular box of length L and with ends each of area A. Because the molecules move in all directions, at any instant one-third of them, $N/3$, might be thought of as moving across the box toward one end or the other. Then if s is the average speed of one of these molecules, it would be expected to travel a distance of $2L$ (from one end to the other and back again) $s/2$ times per second. Because one of these molecules would thus hit one side an average of $s/2L$ times per second, the $N/3$ molecules that are headed in the right direction would hit it $(N/3)(s/2L) = (Ns)/(6L)$ times per second.

As we saw above, the change of velocity of each molecule rebounding from the end is $2s$. Then, if the molecule's mass is m, the change of ***momentum*** (momentum = mass × velocity) is: mass × change of velocity = $m2s$. The total change of momentum per second of molecules striking the end of the box is this change of momentum per rebound times the number of rebounds per second (which we found to be $Ns/6L$); so

$$\text{Change of momentum per second} = 2ms\frac{Ns}{6L} = \frac{Nms^2}{3L}$$

But, according to a relation discovered by Newton (see p. 58), this change of momentum per second is just the force exerted by the molecules on the end of the box. The pressure, then, is this force divided by the area A, so

$$P = \frac{\text{change of momentum per second}}{A} = \frac{Nms^2}{3LA}$$

But LA is the volume of the box, V, so

$$P = \frac{(Nms^2)}{3V} = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}ms^2\right)$$

A more rigorous calculation (much more complicated, too), which takes into account the random motion of the gas molecules, would give the same result as ours with the following exception: The kinetic energy $\frac{1}{2}ms^2$, computed here from the ***average speed,*** would be replaced by $\frac{1}{2}mS^2$, the ***average kinetic energy***—there is a small difference!

The last expression can be rewritten in the form

$$PV = \tfrac{2}{3}N(\tfrac{1}{2}mS^2) = \tfrac{2}{3}\text{ (total molecular kinetic energy)}$$

This would look very much like the general gas law if some quantity on the right-hand side could be called the absolute temperature. From what we now understand, heat is a form of energy, presumably molecular, and the change of quantity of heat energy is proportional to the change of temperature and to the mass being heated. Therefore, it is only natural for us to jump to the conclusion that total molecular kinetic energy and, consequently, the right-hand side of the last equation must depend only on the temperature and the total mass of gas.

Absolute Temperature According to the Kinetic Theory. Our story of molecules and the gas laws fits together beautifully if we consider that heat energy and molecular kinetic energy are the same, and that for gas of a fixed mass this energy depends only on the temperature. The energy of the flying molecules would increase as the temperature is raised, and the motion of the molecules would cease only when the temperature is lowered to absolute zero.

On this basis, the molecular kinetic energy will just be proportional to the absolute temperature T and the mass M of the gas. Using this proportionality, the last equation becomes

$$PV = kMT$$

Here k is a different constant for each kind of gas. This expression now is exactly our original form of the general gas law (page 359).

The basic idea of the kinetic theory of matter, that matter is made of tiny molecules which are in rapid and continual motion, and that absolute temperature merely means something proportional to the average energy of agitation of these moving molecules, thus gives a simple, accurate description of the behavior of gases. As a result, the kinetic theory has been of tremendous importance to scientists. Improvement in agreement between experiment and theoretical predictions has accompanied refinements of the theory to take into account such factors as the size and nature of the molecules themselves and the forces between them. This fact demonstrates the essential "truth" of the kinetic theory, especially as scientists push on into new fields without uncovering anything that contradicts its fundamental ideas.

Gases, Liquids, Solids. The molecules in a gas are comparatively free and move at high speeds until they happen to hit neighboring molecules or surrounding objects such as the walls of containers. After collision, they rebound and go on, sometimes with more, sometimes with less, speed than before.

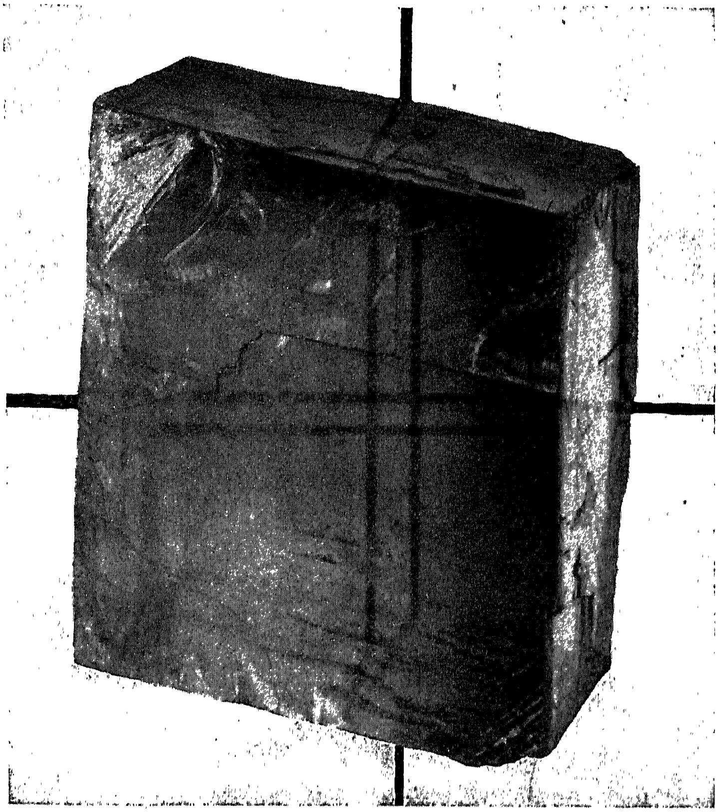
Condensation. If the temperature is lowered steadily, the average energy of motion of the gas molecules is reduced until finally the natural attraction between similar molecules gains control and the gas condenses to a liquid. This temperature, the boiling or vaporization temperature, depends on the kind of molecules and the pressure. In order to make the comparatively free gas molecules go into a liquid state where they are fairly tightly bound together, a considerable amount of energy must be extracted from them. This energy, per kilogram, we call the ***heat of vaporization.*** In a liquid, where the volume is usually about 1,000 times less than in the gaseous state at NTP, molecules have much less freedom and continually are restrained by their neighbors, although they still move about some, each with an average kinetic energy proportional to the absolute temperature—but the constant of proportionality is different for the liquid state from that for the gaseous state.

Freezing. When the temperature of a typical liquid is steadily reduced from its boiling point on down, the average kinetic energy of each molecule becomes less and less until finally, at the fusion point, the attractive forces between the molecules "take over" completely. The molecules then stick together in the solid state, where they are free only to vibrate back and forth about fixed positions. Some additional energy must be extracted to force the molecules into this restricted state. This energy, per kilogram, is the ***heat of fusion*** of the material.

Naturally, in order to perform the reverse changes of state, and to free the molecules from the solid state (that is, to melt the solid), or to pull molecules from the liquid state so that they are free to bounce around as gas molecules, energy equal to the heat of fusion or vaporization must be ***added*** to each kilogram of substance—as we learned in Chap. VII.

Crystals. Practically always, when molecules come together to form a solid, they group themselves in regular arrangements, or ***crystals,*** whose shape depends on the nature of the forces which neighboring atoms exert on each other. Atoms of elements like iron or nickel, or

molecules of certain compounds like sodium chloride, tend to group themselves in a simple cubic form. As we have learned (page 191) ordinary table salt (NaCl) looks like little cubes when examined under a microscope, and under favorable conditions crystals of

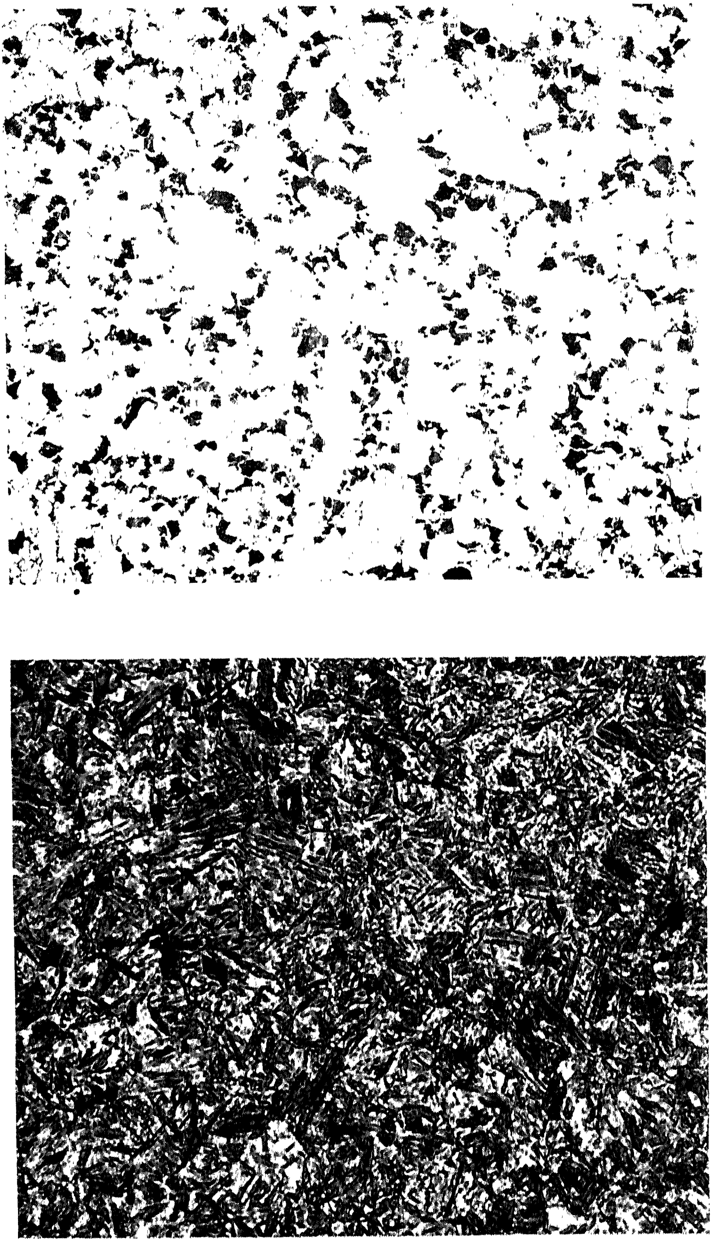


(*English, Getting Acquainted with Minerals.*)

Fig. 266. Calcite crystal showing double image.

sodium chloride may grow to be many inches or even one foot along an edge.

Many types of crystal structure are found, ranging from the simple cubic to the rhombic form such as calcite (calcium carbonate, $CaCO_3$), to tetragonal, hexagonal, and even more complex and beautiful forms. We saw some of these types in Figs. 127–131. The size and type of crystal are very important to the metallurgist, chemist, and physicist, because many properties, such as strength, magnetic qualities, electrical conductivity, and optical properties



(a) (b)

(*General Motors Company.*)

Fig. 267. Properties of materials depend markedly on structure. Microphotograph of: (a) case-hardened steel, 100 diameters; (b) carburized steel.

such as refraction, depend on the crystalline structure. The geologist finds crystal structure useful to help identify compounds and minerals.

Crystals might well be called giant molecules, for they are regular arrangements of individual atoms and molecules built up to large size, and their shape mirrors the nature of these individual particles of which they are composed. It is doubtful if there are many truly *amorphous* solids, without any definite form, for X rays reveal evidence of some organized structure in nearly everything, including liquids.

MORE ABOUT MOLECULES

The picture of speeding gas molecules producing pressure as they bump into walls and incidentally into each other may seem quite reasonable, but it is even more convincing if we can answer questions about how many molecules there are in a certain sample, how big they are, and how fast they are moving.

How Big Are Molecules? Some idea of molecular sizes can be obtained very easily. Molecules cannot be seen by the best optical microscopes, so they are less than 1/10,000 cm in diameter. A very tiny droplet of oil somewhat less than 1/1,000 cm^3 will spread out on water to give a film covering an area of more than 1,000 cm^2. Since the film can hardly be less than one molecule thick, simple arithmetic shows that the diameter of an oil molecule cannot be greater than 10^{-6} cm. The amount of soap solution in a bubble shows that some soap films are less than 5×10^{-7} cm thick; so these molecules must be at least this small.

To make more accurate estimates of molecular sizes, it has been necessary to use Avogadro's explanation of the work of Dalton, Boyle, and Lavoisier, in which he showed that equal volumes of gases at the same temperature and pressure contain the same number of molecules. Even with this information, physicists and chemists had to wait until Faraday had performed his experiments on electrolysis, and until the electric charge on an electron was measured, before they were finally able to tell accurately how many molecules of air, or of any other gas, there are in a cubic centimeter under standard conditions (usually NTP—0°C and 76 cm Hg). Measurements on the buffeting of particles by flying

molecules in the Brownian motion also have given an estimate of the number of gas molecules in one cubic centimeter at NTP.

This number is 2.7×10^{19} or 27,000,000,000,000,000,000 molecules in *one cubic centimeter* of gas at NTP![1]

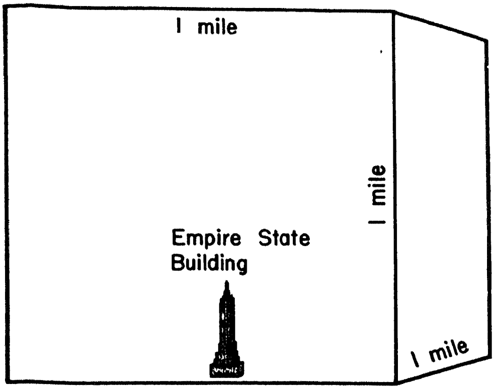


Fig. 268. There are 2.7×10^{19} molecules in 1 cc of gas at NTP. This number of grains of sand packed tightly would fill a cube one mile on each side!

This seems like a tremendous number, and indeed it is. It is so large that if this number of grains of sand were tightly packed they would form a huge cube of sand with each side more than one mile long! Even so, the molecules in a gas are so tiny that they fly about in almost empty space. Only when kinetic energy is taken from molecules so that they condense from a gas to a liquid are they closely packed, and then the volume occupied is about 1/1,000 of what it would be for the gas under normal conditions.

The number of molecules in the liquid state is the same as the number of molecules of gas which condense, and that can be calculated from the volume, temperature, and pressure of the gas before, and again after, part of it is liquefied. For ordinary oxygen, O_2, there are about 2×10^{22} molecules in 1 cm^3 of the liquid. Using this number, a little simple arithmetic shows that the diameter of the oxygen molecule must be only about 3×10^{-8} or 1/30,000,000 cm.

[1] One sees more frequently the equivalent statement that there are 6.03×10^{23} molecules in one gram-molecular weight of any material, or in 22.4 liters of gas at NTP. This number is called *Avogadro's number*. One gram-molecular weight of hydrogen gas, H_2 (atomic weight 1, molecular weight 2), or 2 grams of H_2, then would contain 6.03×10^{23} molecules. For oxygen, O_2 (atomic weight 16, molecular weight 32), 32 grams of O_2 would contain the same number of molecules.

In spite of the tiny size and complete invisibility of molecules, the physicist has been able to find ways of weighing single molecules and atoms, of determining their size and speed, and even of investigating their internal structure.

Speeding Molecules. How fast are the air molecules really going as they continually bombard us? Even though there are 27 billion billion air molecules in a cubic centimeter, they weigh so little that they must travel with the speed of low-power rifle bullets in order to produce ordinary atmospheric pressure! We have seen (page 361) that the pressure produced by rebounding molecules when they rain on a surface can be expressed

$$\text{Pressure} = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}\,mS^2\right) = \frac{1}{3}\frac{N}{V}\,mS^2$$

Since Nm/V is just the total mass/volume, or the ***density*** (see page 151), the pressure may also be expressed

$$\text{Pressure} = \tfrac{1}{3}\text{ density} \times S^2$$

If the appropriate numbers for ordinary oxygen (O_2) which is in the air, are put in the last expression, it is found that the average speed of the molecules must be roughly 1,600 ft/sec or 525 meters/sec!

Physicists and chemists who work with gases have reached the conclusion that the average ***kinetic energy, $\frac{1}{2}mS^2$, of all kinds of molecules at the same temperature must be the same.***[1] The only

[1] We recall (p. 360) that for one gram-molecular weight of any gas

$$PV = KT$$

where K is the same for all gases. If Joule's equation (p. 361) applies to one gram-molecular weight of gas, or to N_0 molecules of the gas, it becomes

$$PV = \tfrac{2}{3}N_0(\tfrac{1}{2}mS^2)$$

Comparing these two equations, we see that

$$PV = KT = \tfrac{2}{3}N_0(\tfrac{1}{2}mS^2)$$

or

$$T = \frac{2N_0}{3K}\left(\frac{1}{2}\,mS^2\right)$$

But N_0 and K are constants for all gases; so

$$T = (\text{constant})(\tfrac{1}{2}mS^2)$$

which is another way of saying, not only that the absolute temperature of a gas is directly proportional to its kinetic energy per molecule, but that the kinetic energy per molecule is the same for all gases at the same temperature.

way this can be true is that heavier molecules move slower and lighter molecules move faster, so that the average of the product mass × speed^2 is the same for all. For example, the oxygen molecule O_2 has a mass 16 times as great as the hydrogen molecule H_2, because the relative atomic weight of oxygen is 16 and that of hydrogen is 1. In order for

$$\text{Average KE} = \tfrac{1}{2}mS^2$$

to be the same, we see that

$$\tfrac{1}{2}32(S_O)^2 = \tfrac{1}{2}2(S_H)^2$$

where the left-hand side applies to oxygen and the right-hand side to hydrogen. This gives

$$(S_H)^2 = 16(S_O)^2, \qquad \text{or} \qquad S_H = 4S_O$$

In other words, the ***average speed of the hydrogen molecule must be about four times as great as that of the oxygen molecule*** at the same temperature.

Distribution of Molecular Speeds. Long before any direct experimental proof of large molecular speeds was possible, when many chemists and physicists were not at all convinced that molecules even existed, such great mathematical physicists as James Clerk Maxwell (1831–1879) in England and Ludwig Boltzmann (1844–1906) in Germany were developing a mathematical basis for the kinetic theory of gases, and to some extent for liquids and solids.

One of Maxwell's ideas that had far-reaching applications is his concept of the distribution of molecular velocities. Because gas molecules bump into the walls of containers and into each other, thereby continually changing their individual velocities, the velocities from molecule to molecule differ greatly at any given instant. Maxwell applied the laws of chance to predict what would happen if the motion and the collisions of the molecules were purely random. He expressed his results in a mathematical equation which we need not consider because a graph illustrating these results is sufficiently instructive.

The solid-line graph of Fig. 270 gives, for nitrogen at 0°C, the relative chances for a molecule to have the speeds indicated on the horizontal scale. This is also the relative number of molecules having the various speeds shown. A curve of this same shape, but with

a different horizontal scale, would hold for any gas at any temperature. The speed corresponding to the peak of the solid curve (400 meters/sec for N_2 at 0°C) is the most probable value. At any instant most of the molecules of a gas have speeds somewhere in the neighborhood of the most probable speed, but a few may have

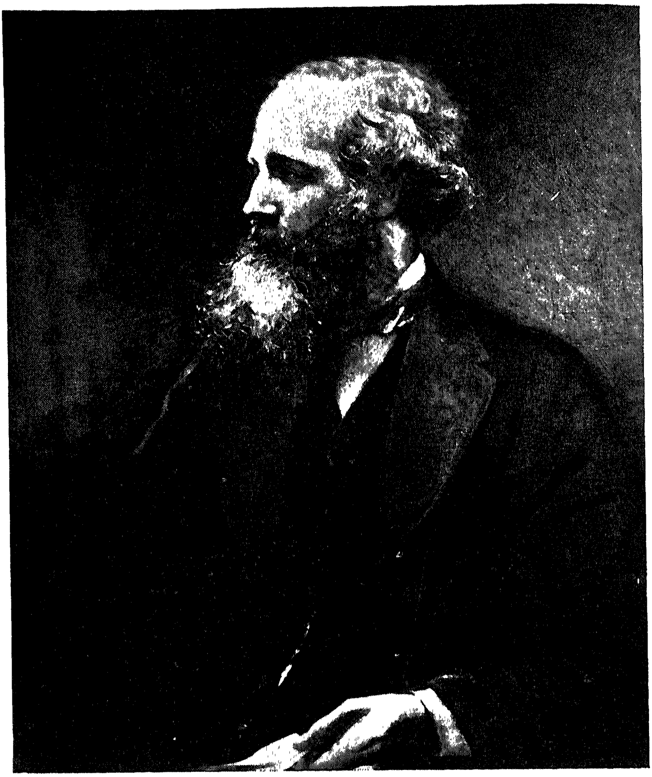


Fig. 269. James Clerk Maxwell.

very high speeds and a few others practically zero speed. There is no real limit to the speed, but the numbers of molecules having higher and higher speeds simply get smaller and smaller. Theoretically, some molecules might have nearly infinite speed, but the probability is so small it need not be considered. As a gas is cooled, the average speed would be lowered as shown by the dotted curve of Fig. 270.

Statistics. Considerations such as Maxwell used for determining the distribution of molecular speeds find wide application today in many diverse phenomena, ranging from the behavior of atoms,

molecules, and electrons to that of living organisms, and including all sorts of data connected with people, industrial production, and business. The usefulness of statistical analysis in these varied fields is based on the essential ideas of probability which Maxwell, Poisson, Gauss, and many others have helped to work out.

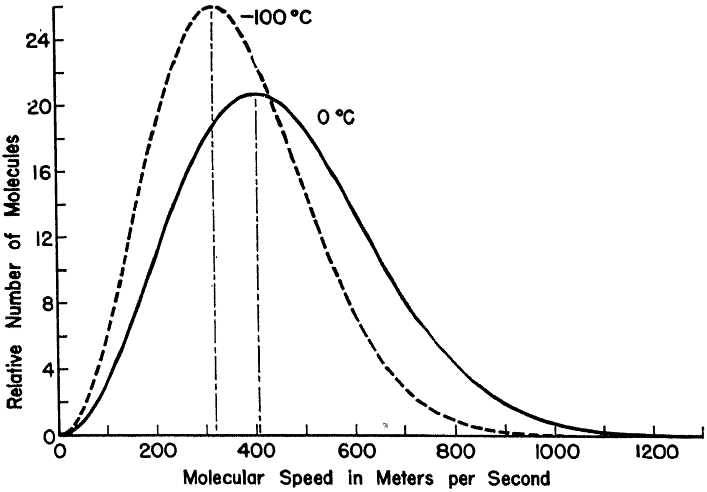


Fig. 270. Maxwell's curves showing the distribution of molecular speeds in nitrogen at 0°C and −100°C. It can be seen from the solid curve, for example, that at 0°C there are about twice as many nitrogen molecules with speeds between 350 and 450 meters/sec as in either the range between 150 and 250 meters/sec or between 600 and 700 meters./sec. In other words molecular speeds between 350 and 450 meters/sec are about twice as probable as those in either of the other two ranges.

Most distributions of individual things which depend upon chance follow some curve such as Maxwell's. Actually, more generally used to represent "chance" distribution is the so-called "error curve," a symmetrical distribution calculated by Gauss.[1] As an example of a typical distribution curve, let us take the distribution of height among adult males. The data follow a curve much like that in Fig. 271a,b.

The distribution of intelligence among people (as best it can be measured) has much the same form; most persons are near the average, but a few are geniuses while a few others are imbeciles. To some extent, at least, a series of measurements of any quantity

[1] Gauss's distribution would apply to molecular speeds along any one line, Maxwell's equation to speeds in all directions.

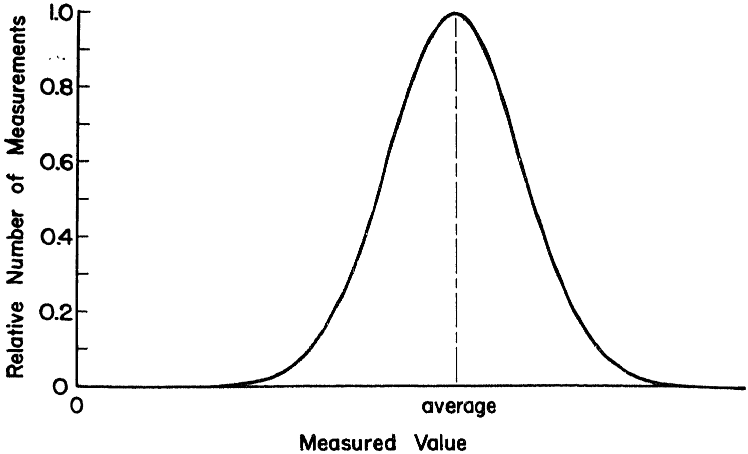
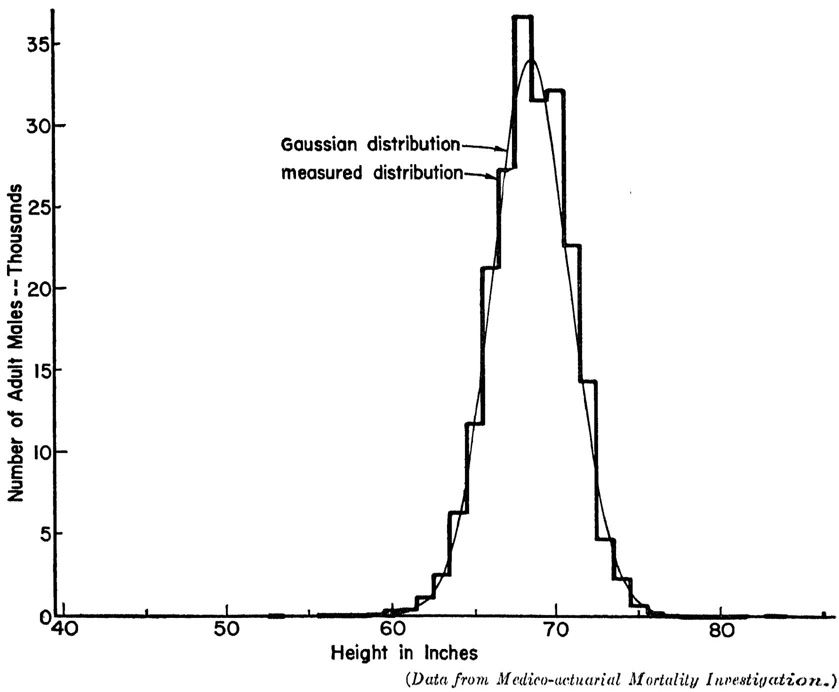


Fig. 271a. Gauss's distribution curve. Frequently taken to represent chance deviations of individual measurements from the average value.



(*Data from Medico-actuarial Mortality Investigation.*)

Fig. 271b. Distribution of heights of about 200,000 adult males.

is subject to chance variation, and so is influenced by a similar distribution. The grades of this class usually follow such a distribution curve fairly well.

Of course, one must be very careful in drawing general conclusions from statistics unless the measurements are made on a ***large*** number of individuals. A single individual can belong to any part of a distribution, and one must "sample" many individuals in order to predict this distribution or get a significant average. When measurements are made on individual things such as atoms or electrons, the statistical ***probable error*** of the average result, that is, the error expected from "chance" deviations, is approximately proportional to the ***square root*** of the number of individuals tested.

For example, if by means of a "perfect" atom counter the number of atoms passing a point in some time interval could be determined and if only 4 were counted, the result would be considered reliable only to within $4 \pm \sqrt{4}$ (between $4 - \sqrt{4}$ and $4 + \sqrt{4}$), or 4 ± 2; that is, the chances are better than even that the "true" result would be between 2 and 6. If 100 were counted, this result would probably be accurate to within 10 out of 100, or within 10 per cent. A count of 10,000 would have a probable error of 100 out of 10,000, or 1 per cent, etc. The percentage accuracy increases with the number measured, but only slowly. If high accuracy is desired, very many individuals must be considered.

Of course there are always additional sources of error in measurements, because every instrument and every observer have limitations. The errors so introduced must also be taken into account when they are appreciable as compared with the statistical probable error. We shall meet this problem of accuracy in measurement many times, particularly when we learn more about individual atoms and electrons.

Many statistical analyses are quite complicated and beyond the scope of this discussion. In the polls conducted by Dr. George Gallup and others, which are now so popular, properly "weighted" sampling must be done so that all population groups are correctly represented. If properly selected, a sample group of 10,000 individuals will give a reasonably accurate picture of the attitude of the whole 140 million people in this country. The small increase in accuracy realized by going beyond this would usually not warrant the trouble required to obtain it.

The concepts of the kinetic theory worked so well to explain phenomena in nature that they were gradually accepted and used. However, many years had to elapse before experimental techniques developed to the point where Maxwell's and Boltzmann's pioneering ideas could be directly tested on molecules. Professor Otto Stern, now at Pittsburgh, showed less than twenty years ago that molecules did indeed have a distribution of speeds just as predicted. The essential procedure was to time the flight of molecules over a measured distance, just as the speeds of runners between the start and finish lines can be determined by means of stop watches. The results were in excellent agreement with the theoretical curve of Fig. 270.

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SUMMARY

Joule concluded that gas pressure is the result of bombardment by continually moving gas molecules. ***Brownian motion*** gives direct support to this idea.

$$\text{Pressure} = \text{force/area, in lb/in}^2 \text{ or newtons/meter}^2.$$

The pressure at the bottom of a column of gas or liquid is (height of column) $\times$ (density of fluid) $\times$ g. Normal atmospheric pressure is about 15 lb/in^2. Pressure exerted on an enclosed gas or liquid is transmitted equally throughout the material.

A mercury barometer balances atmospheric pressure against a column of mercury (about 76 cm high). Thus "centimeters of mercury" is used as a pressure unit. Barometric pressure decreases with increasing altitude and may be affected by weather changes. A more compact barometer is the aneroid type.

Mercury manometer or bourdon gages may be used to measure pressure. Total pressure is usually obtained by adding the value of the atmospheric pressure to the gage reading.

The "gas laws" follow: (1) Boyle discovered that the pressure of a definite mass of gas is inversely proportional to its volume if the temperature is not changed. (2) From a discovery by Charles and Gay-Lussac, the pressure of a gas of fixed mass and volume is directly proportional to its ***absolute*** or ***kelvin*** temperature (centigrade temperature +273). (3) The volume of a fixed mass of gas is directly proportional to the absolute temperature if the pressure is not changed. Laws 2 and 3 hold only if the temperature is well above the condensation point of the gas.

A general relation that embodies the above three "gas laws" involves the pressure P, volume V, absolute temperature T, and mass M of a gas. It is

$$PV = kMT$$

where k is a constant for each kind of gas. If M is always made one ***gram-molecular weight,***

$$PV = KT,$$

where K is the same constant for all gases.

The pressure exerted by the moving molecules of a gas, times the volume can be shown to be

$$PV = \frac{2}{3} N \left(\frac{1}{2} mS^2\right)$$

where N is the number of molecules and $\frac{1}{2}mS^2$ is the kinetic energy per molecule. As $N(\frac{1}{2}mS^2)$ is the total molecular kinetic energy or just the heat energy of the gas, it should be proportional to the product of the mass and temperature. Making use of this proportionality, the last theoretical expression agrees with the experimental relation $PV = kMT$.

When the temperature of a gas is lowered, the molecular speeds are reduced, so attractive forces between the molecules eventually gain control and the gas condenses to liquid; freezing represents a further stage. Energy (heats of fusion and vaporization for each kilogram) must be removed to make these changes of state, or added to make the reverse changes.

Any gas at NTP consists of 2.7×10^{19} molecules per cubic centimeter. The diameter of an O_2 molecule is about 3×10^{-8} cm, estimated from the condensed volume.

For all gases and solids, the absolute temperature is directly proportional to the kinetic energy per molecule ($\frac{1}{2}mS^2$).

The individual speeds of molecules in a gas are grouped about the average value according to a "chance" distribution which was calculated by Maxwell. Either this distribution, or the "error curve" due to Gauss, applies generally to statistics which depend purely on chance.

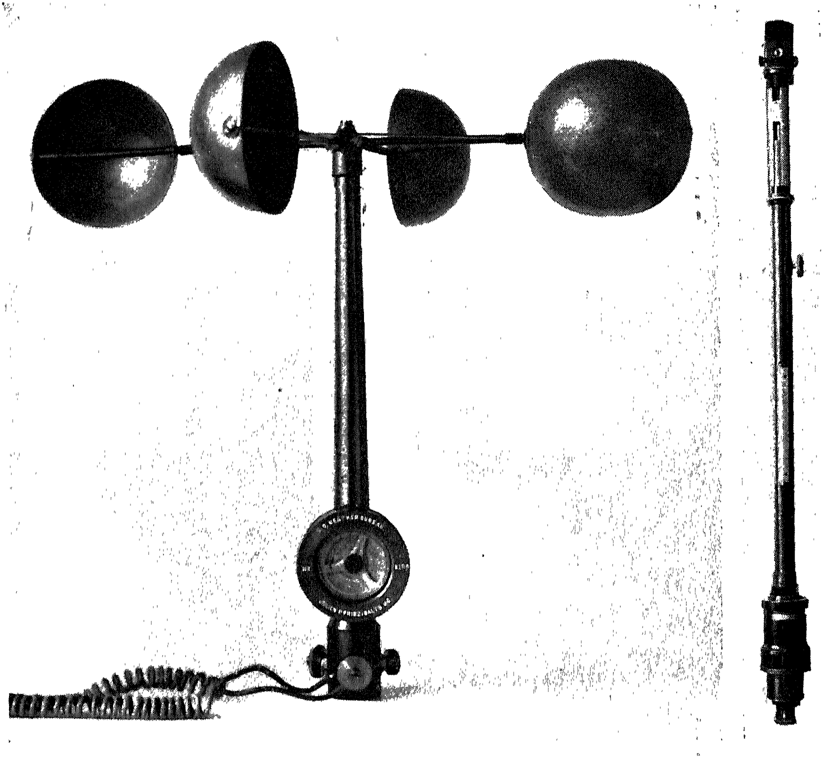
QUESTIONS

1. How did the first experimental evidence of the particle nature of matter grow out of the work of Dalton, Boyle, and Avogadro?
2. How certain is our experimental basis for the belief that the molecules of all matter are in rapid and continual motion, and that temperature is simply a measure of the average kinetic energy, $\frac{1}{2}mS^2$, of the molecules?
3. How can we measure the effect of a large number of molecules if we cannot know what is happening to every one of them at a particular time?
4. Why are our experimental and theoretical studies of matter in general only statistical?
5. How does the continual jerky motion of microscopic pollen grains, first observed by Brown, show the behavior of the molecules buffeting them about? Do we see the molecules themselves?
6. How much faster must a helium molecule, He, travel than an oxygen molecule, O_2, in order that the kinetic energy shall be the same?
7. How well do gases follow Boyle's law? Are there any assumptions involved in Boyle's law that are not quite correct?
8. What is the absolute or kelvin scale of temperature?
9. Why are the characteristics of a nearly perfect gas such as hydrogen useful in thermometry?
10. How do we use the gas laws in actual problems? What are the limitations of the general gas law?
11. A quart jar is sealed with air in it at 32°F and 76 cm Hg. What is the pressure in the jar after it is placed in water which is "brought to a boil"?
12. The density of air at 74.6 cm Hg and 24°C is measured as 1.155 kg/meter^3. To what density at NTP does this correspond?
13. The U. S. Army's stratosphere balloon, "Explorer II," had a gas bag with a capacity of 3,700,000 ft^3. How many cubic feet of helium at NTP had to be available for the inflation so that the bag would be completely expanded at an altitude of about 12 miles where the atmospheric pressure is 4.5 cm Hg and the helium temperature would be −30°C?
14. Are all the molecules of a gas moving alike at any instant?
15. The pressure in a good X-ray tube may be as low as 0.0000001 mm of Hg. How many molecules are still present per cubic centimeter, if there are about 27×10^{18} molecules/cm^3 at 760 mm Hg?
16. What does a typical Maxwell distribution curve show us regarding the distribution of molecular speeds? Do any gas molecules have zero speed?
17. Would the predictions of a distribution curve such as Maxwell's be accurate if we had only ten molecules with which to deal? Why must we have large numbers of individuals in order to agree with theoretical distributions?
18. How are the ideas underlying the distribution of molecular velocities and other features of molecular motion applicable to other fields?

CHAPTER XIII

SCIENCE AND THE WEATHER

Weather Forecasting. In 1869, Cleveland Abbe began to make regular weather predictions for the vicinity of Cincinnati. He had

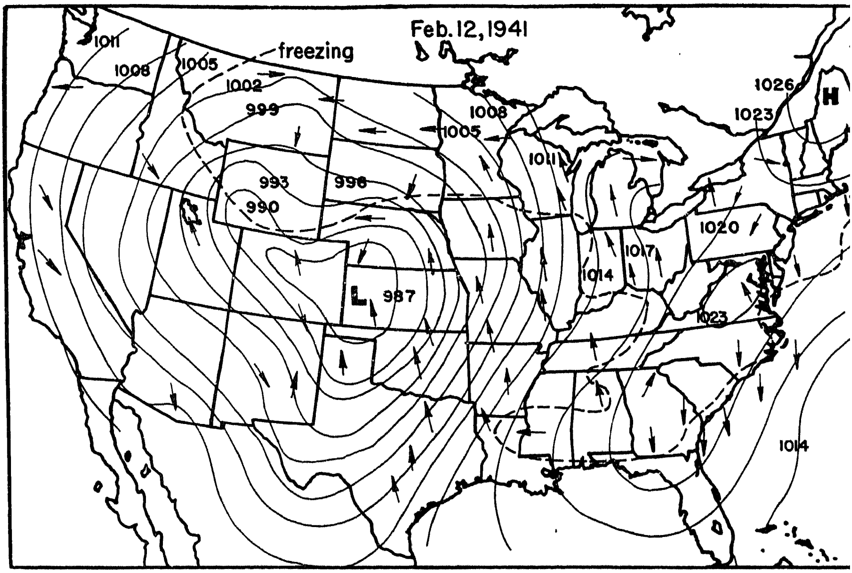


(a) (b)

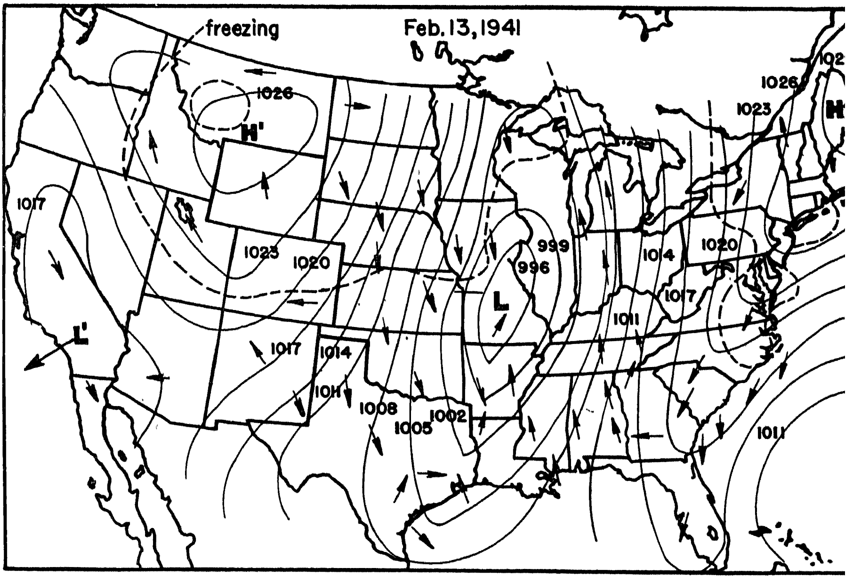
(*U.S. Weather Bureau.*)

Fig. 272. (a) Anemometer, for measuring wind velocity; (b) mercury barometer.

enough success to encourage a similar Federal program, and the forerunner of the United States Weather Bureau was initiated in Washington the following year.



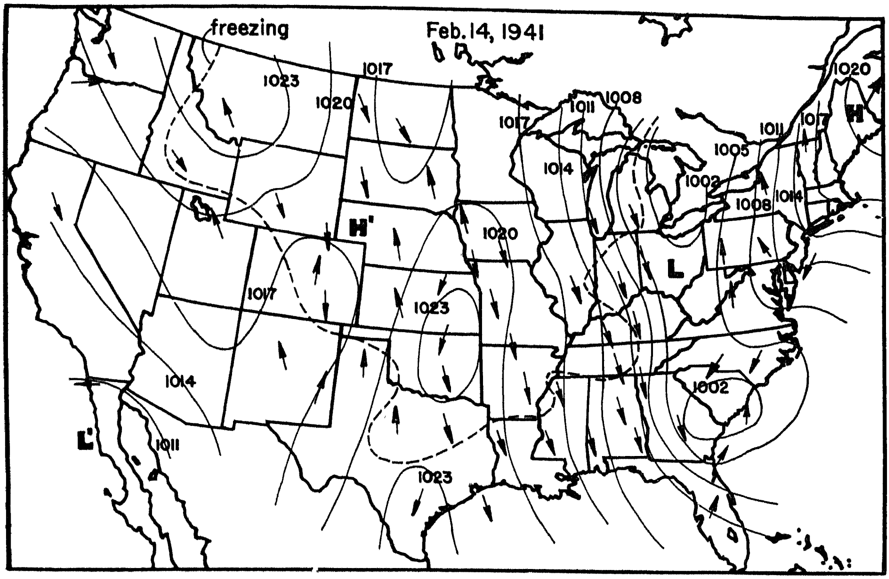
(a)



(b)

Fig. 273. For legend see opposite page.

Weather students, or meteorologists as they are called, are far from being seers or astrologers. The possibility of moderately accurate prediction has resulted from scientific study of the atmosphere. This involves extensive regular observations of such



(c)

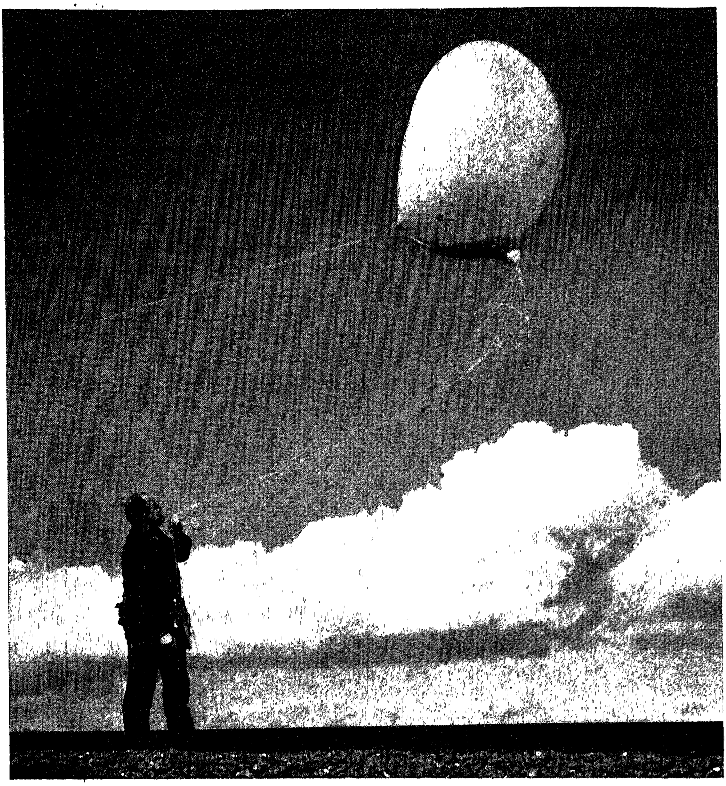
Fig. 273. Weather maps for three successive days. The barometric pressure for each "isobar," i.e., line of constant pressure, is given in millibars (page 350). Arrows indicate wind directions. The dotted line passes through points of temperature 0°C.

Alternate regions of high (H and H′) and low (L and L′) barometric pressure tend to travel across the United States from west to east. Note in (c) that the low L appears to be breaking up.

factors as barometric pressure, wind velocities at various altitudes, rainfall or snowfall, moisture content of the air, cloud types, and degree of cloudiness. The results of these observations, when mapped daily and followed over long periods, have shown a more or less regular "unfolding" of weather conditions. In any single instance, the sequence to be expected depends upon the geographical region, the time of the year, and the general conditions shown by a weather map. From Fig. 273, for example, we see that a sequence of atmospheric pressure changes at one spot is understandable in terms of the travel of regions of high and low barometric pressure (*H* and *L*) from west to east.

The daily collecting of weather observations from many stations and the immediate analysis of data in order to predict the following

day's weather make a story of almost unmatched cooperation and efficiency. In a later chapter of this story is described the vital concern of air transport companies with weather conditions and predictions, and the vast network of weather reporting stations



(U.S. Department of Agriculture photograph by Radford.)

Fig. 274. "Radio sounding" apparatus carried by balloons into the air automatically signals weather conditions to observers on earth.

which these companies have set up in cooperation with the government.

"Radio sounding balloons," after release, automatically send back from miniature transmitters signals that reveal pressure, wind, and temperature conditions in the upper atmosphere. Because of instruments such as these, predictions now are being based more and more on "air mass movements" at various levels in the atmosphere. As increasing data have been made available to meteorologists, the effectiveness of weather forecasting has improved steadily. Moreover, there is reason to hope that new types of

atmospheric observation and wider accumulation of daily information will increase the accuracy of weather predictions, and possibly even lead to successful "long-range" forecasting.

FACTORS CONTROLLING THE WEATHER

Already we have discussed some of the things which have important effects on climatic or weather conditions. Among these

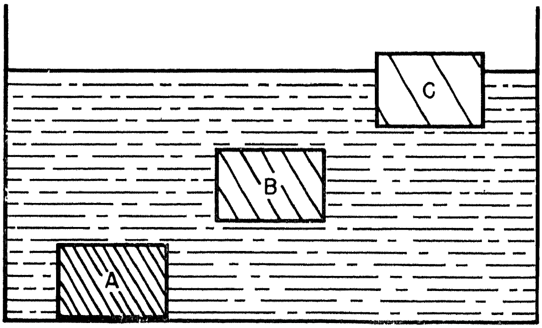


Fig. 275. Buoyancy of fluid. Object A, more dense than the water in which it is immersed, sinks to the bottom. B, of the same density as the water, can remain at any level. C, less dense than the water, floats at such a level that the buoyant force exerted on it by the water just equals its weight. (We recall, Fig. 12, page 25, that the buoyant force equals the weight of water displaced by an object, hence the less dense C is, the higher it will float.)

was Copernicus's "explanation" of the seasons, which accounts for annual weather cycles (page 45). Also we have learned that the important influence of large bodies of water on atmospheric temperature is due to the high specific heat of water as compared with that of land (page 233). Further, we have become acquainted with the interpretation of barometric pressure as the weight of a certain vertical column of the atmosphere (page 348). An additional fact of great importance is that matter of lower density tends to rise to the top of a denser fluid. This was implied when we reasoned that bodies of water should commence to freeze at the top rather than at the bottom (page 167).

Buoyancy. The latter effect illustrates "buoyancy" of fluids, which was studied in detail by Archimedes. It is a process which has an important influence on the weather. Let us recall some of the better known results of the buoyancy of liquids and gases: Bubbles rise to the surface of boiling water; hydrogen- or helium-filled balloons

rise in the air to a certain level; smoke rises when the atmosphere is dense, that is, when the barometric pressure is high, but falls when the barometric pressure is low; a nationally advertised soap rises to the surface after being dropped in water; if part of the air

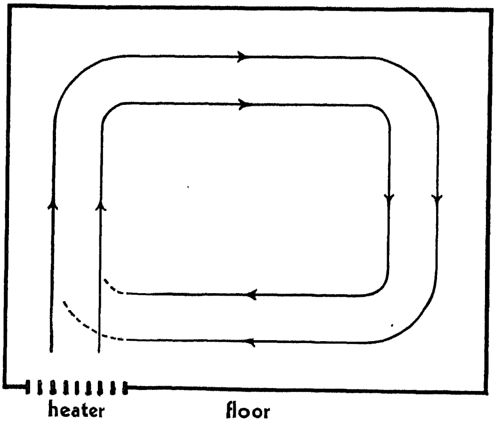


Fig. 276. Circulation of air in a room by convection.

in a room is warmed, it rises to the top of the room, while cold air from a window streams to the floor. In each case, the matter which rises is less dense than the surrounding fluid. In fact, the upward or buoyant force on some object immersed in a fluid is just the weight of the amount of surrounding fluid that would occupy the volume of the immersed object (Fig. 275). The object rises if its weight is less than this buoyant force, that is, if its density is less than the density of the surrounding fluid, and the object drops if the reverse is true.

Convection in a Room. If we keep in mind these ideas about buoyancy, we can understand how the circulation of air in a room or in a heating system takes place. The air near a heater decreases in density and rises as a result of the increased buoyant force on it; more rising warm air forces that air to the side, where it is cooled, becomes more dense, and falls because of the resulting decrease in buoyant force. Finally, this air flows back to the heater to replace rising warm air in that location. Thus, continuous circulation or *convection* is maintained.

Convection in the Atmosphere. Similar convective effects on a much larger scale occur in the atmosphere, causing surface winds in one direction and high-altitude winds in the opposite

direction. For example, the sun beats down on the equatorial belt, with the result that an air mass near the earth's surface is heated, expands, rises, flows outward (as high-latitude winds), eventually becomes cooled enough to fall, then moves back toward the

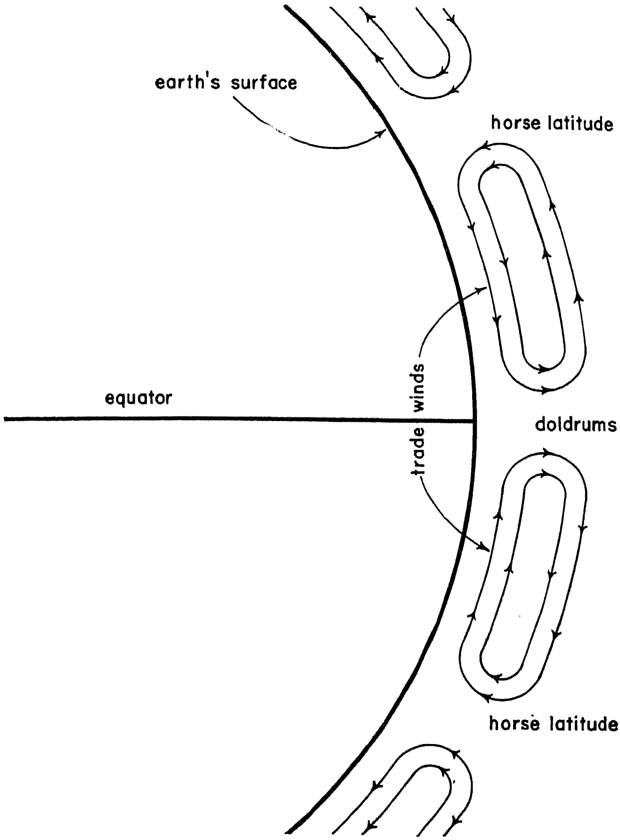
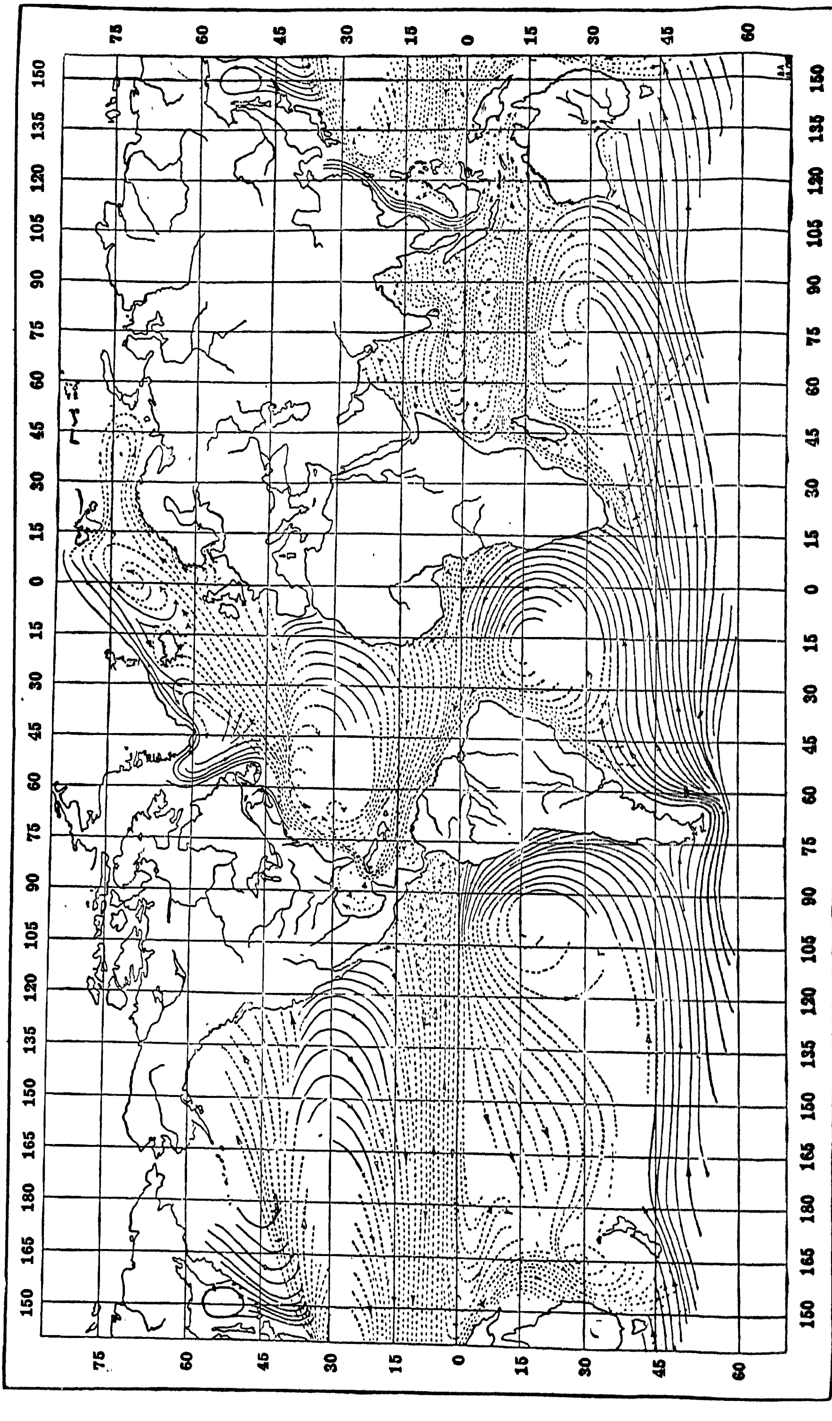


Fig. 277. Convectional circulation of air over the equatorial belt. The high altitude winds and surface winds blow in opposite directions.

equator (as surface winds) to replace more rising warm air (Fig. 277). The "trade winds," which prevail in the northern and southern parts of the torrid zone, and the prevailing "westerlies" of the temperate zones are simply parts of great convectional air currents, modified, as we shall see later, by the earth's rotation.

Temperature differences between adjacent land and water, which are set up because land has a lower specific heat than water, give rise to the coastal convection currents of air that we recognize



(W. J. Humphreys.)

Fig. 278. Ocean currents.

as characteristic shore winds. Thus, coastal breezes tend to blow from water to land when the heating effect of the sun is greatest and in the reverse direction when the sun is obscured.

We may summarize what has been said about convection air

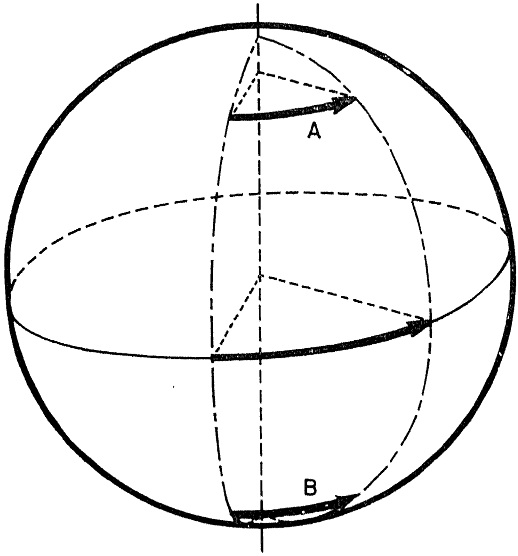


Fig. 279. The earth's rotation "deflects" north-south winds (see next page). Points on the equator travel faster as the result of the earth's rotation than do points on the earth nearer the poles (as at A or B).

currents in the statement that surface winds tend to blow toward a part of the earth which is kept at a higher temperature than its neighboring parts. Where an air mass is heated it becomes less dense, so the barometric pressure drops. Consequently, in terms of pressure instead of temperature, we may say that surface winds tend to blow from a region of high barometric pressure to one of low pressure.

Ocean Currents. The regular, or nontidal, ocean currents are very important in determining coastal climates. For example, they have much to do with the very different climates of Laborador and the British Isles which are at nearly the same latitude. These currents, like those in the air, depend upon energy from the sun. The surface water in tropical seas is warmed by the sun, so it expands and tends to rise in level. Hence it flows outward, uncovering cooler water which in turn is warmed, and thus the process is maintained continuously. Actually, land boundaries play an impor-

tant part in guiding the currents, such as the Gulf Stream and the Japanese Current, which are thus set up.

Cyclones, Hurricanes, and Tornadoes. In the temperate zones, warm currents of air which start toward the poles are deflected eastward

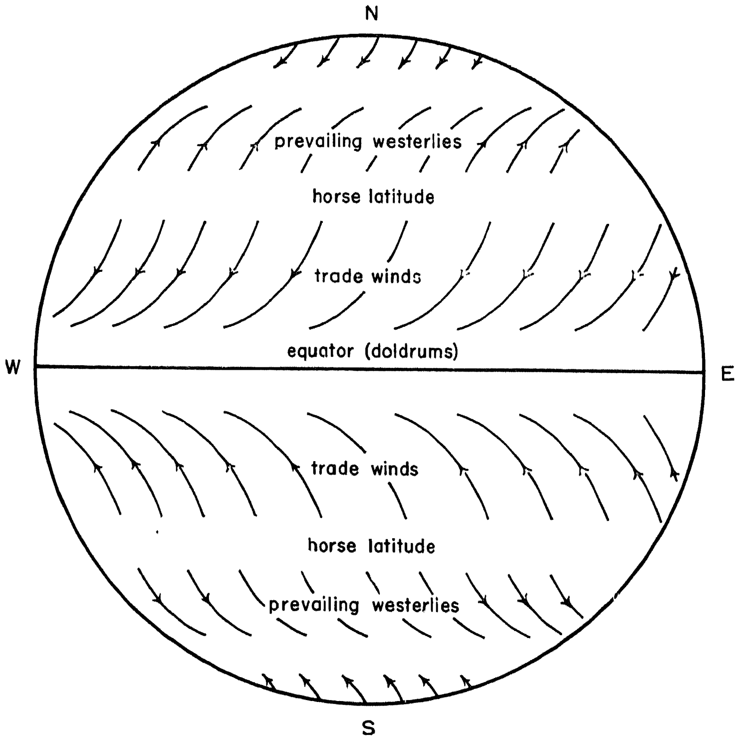
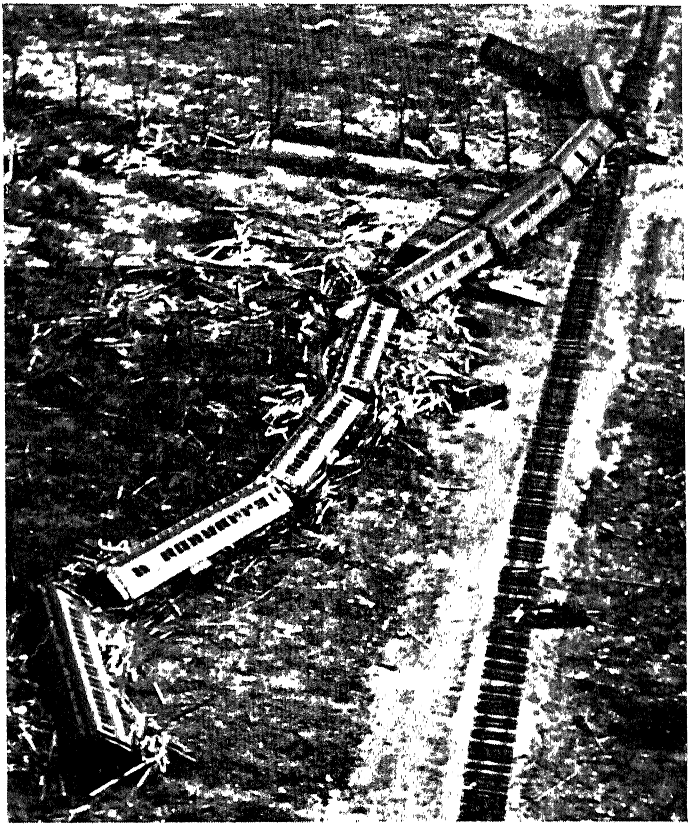


Fig. 280. The earth's rotation modifies directions of the north-south convectional winds.

because of the earth's rotation (hence the name "prevailing westerlies"), and cold winds from the polar regions are turned toward the west. This comes about from the fact, illustrated in Fig. 279, that surface speeds of the earth resulting from its rotation are lower near the poles than at the equator. Wind blowing "northward" at the equator, for example, actually is also following the eastward motion of the earth's surface. That is, anyone on the earth's surface says that this wind is directed northward, but to some observer not carried along by the earth's rotation it would appear to be blowing *northeast*. Then, when the wind gets farther north, where the surface speed of the rotating earth is less than at the

equator, the wind, keeping its greater eastward speed component, gains on the earth in that direction, with the result that has been stated (Fig. 280).

Where the warm winds from the equatorial belt and the cold

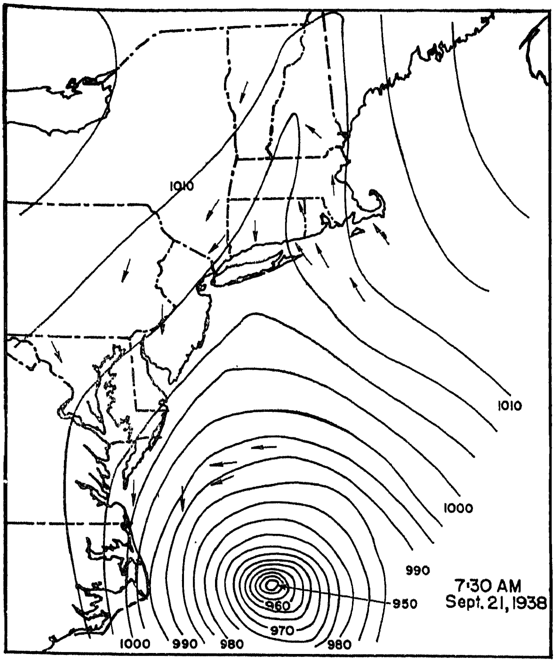


(U.S. Weather Bureau.)

Fig. 281. Effect of wind and water during the hurricane of 1935 in Florida.

winds from the polar region flow past one another (Fig. 280) a pocket of warm air sometimes extends into the cold stream with the result that a huge eddy, from 500 to 1,500 miles across, is formed. In the northern hemisphere, such *cyclones* or *cyclonic storms* are characterized by winds that blow roughly counterclockwise about a region of low barometric pressure. (In the southern hemisphere the rotation is reversed.) Between two successive cyclones is usually a region of high barometric pressure

(a)



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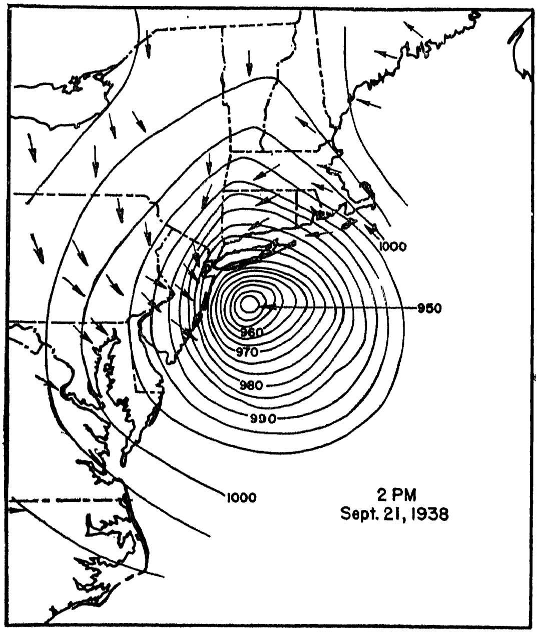
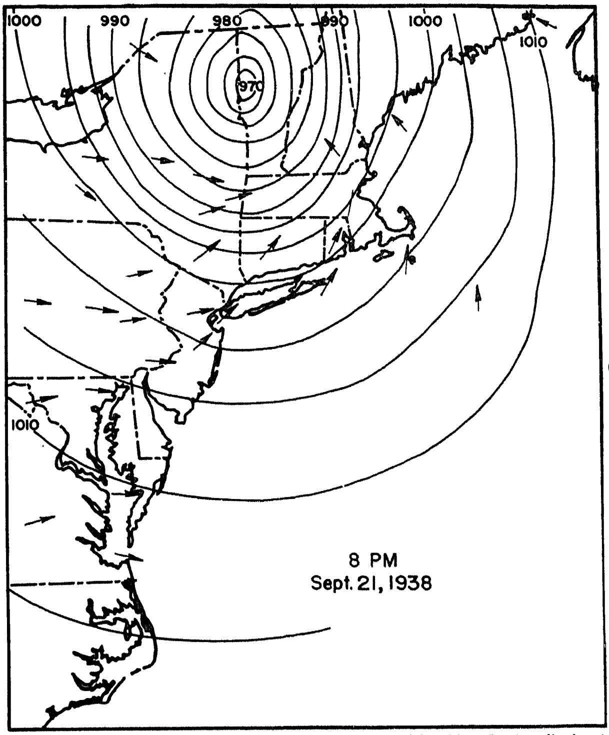


Fig. 282. For legend see opposite page.



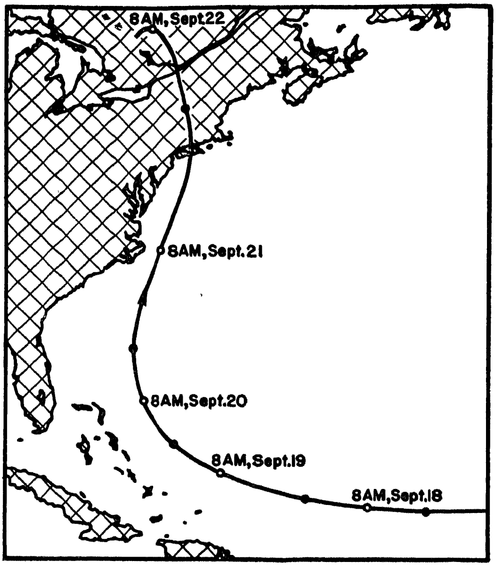
(c)

(After C. H. Pierce, Monthly Weather Review.)

Fig. 282. Weather maps showing form and progress of the destructive hurricane of 1938.

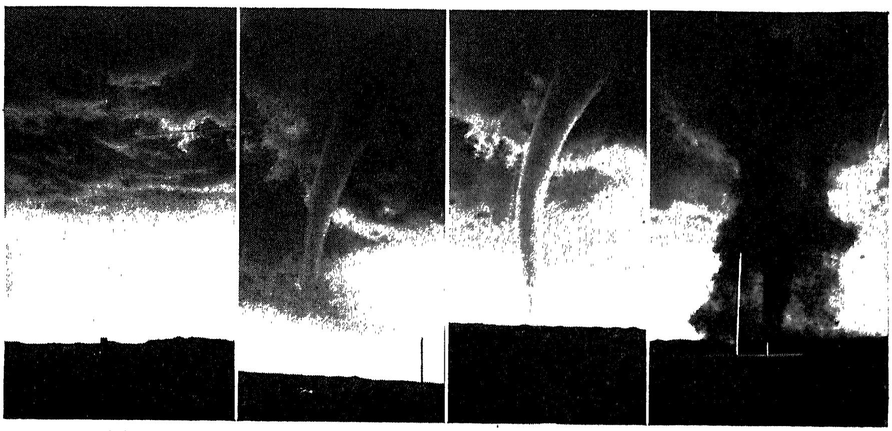
about which mild winds blow with their rotation opposite that of a cyclone. These are called ***anticyclones***. On Fig. 273, region *H* is the center of an anticyclone and *L* is the center of a cyclone. Both cyclones and anticyclones generally travel from west to east.

Other whirling storms, much smaller but of greater severity than cyclones, also are produced by the combined effects of convection and the earth's rotation. One of these, the ***tropical cyclone,*** or ***hurricane*** as it is called in the western hemisphere, is usually only a few hundred miles in diameter but has high, frequently destructive winds which swirl about a central region that may have a barometric pressure of 4 or 5 cm Hg below normal. The progress of the hurricane of September, 1938, from mid-Atlantic, westward, then northward to New England can be traced on the weather maps of Fig. 282. Similar storms which originate east of the Philippines are called ***typhoons***.



(*After C. H. Pierce, Monthly Weather Review.*)

Fig. 283. Path followed by the center of the hurricane of Sept. 1938.



(a) (b) (c) (d)

(*U.S. Weather Bureau.*)

Fig. 284. Tornado near Gothenburg, Nebraska, June 24, 1930. (a) The cone of the tornado drops from turbulent clouds such as these. (b) The cone drops toward earth. (c) The fully developed cone reaches the earth. (d) A farmhouse seems to explode when struck by the tornado.

Sometimes small, extremely violent whirlpools of air are formed in the southern part of cyclonic areas, at a sharp boundary between hot and cold winds. These most destructive of storms are called *tornadoes* when over land and *waterspouts* when over the sea. There is some evidence that tornadoes are formed from horizontal whirls of air which become unstable and drop an extension toward the earth.

Water Vapor in the Atmosphere. We have not mentioned perhaps the most impressive offspring of a storm, that is, the condensation

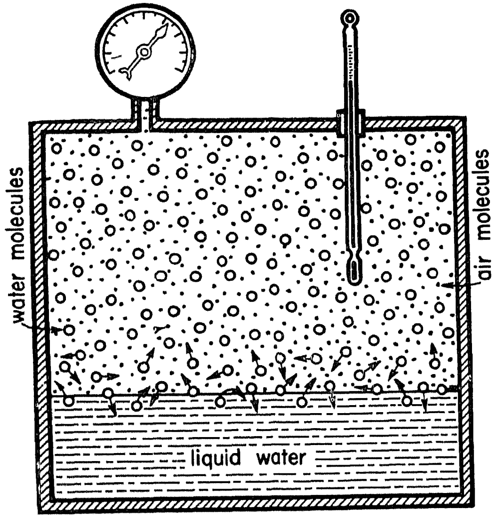


Fig. 285. The vapor above the liquid water is saturated when the rate at which water molecules return to the liquid from the vapor equals the rate at which molecules evaporate from the liquid. We should realize that atoms and ordinary molecules are much too small to be seen even by the best microscopes. Illustrations such as this are purely for the purpose of helping to visualize processes.

of water to form clouds, rain, snow, and so forth. To understand better the role of water in the atmosphere, let us first think of conditions in a closed container holding a little water. The space over the water contains water vapor at the *saturation pressure.* This pressure depends only on the temperature, and increases with temperature. The water vapor alone has the same pressure whether or not air (or any other gas) is in the space with it. The higher the

temperature, the more water vapor occupies the space, and the greater is its pressure (still the saturation pressure). To make this change possible, more water evaporates when the temperature rises, and when the temperature drops, some of the water vapor condenses.

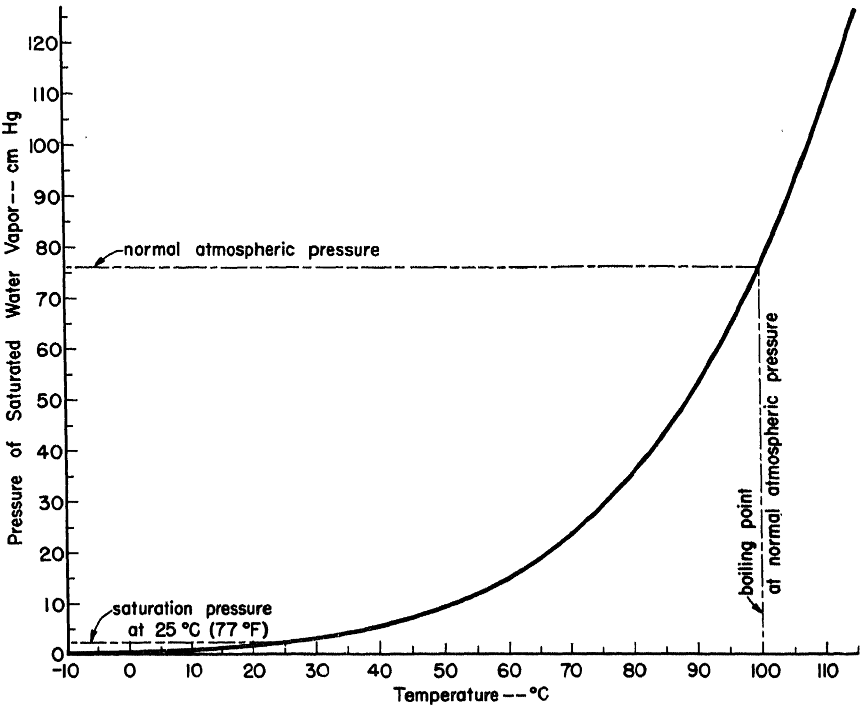


Fig. 286. The saturation pressure of water vapor increases rapidly as the temperature increases. When the saturation pressure equals the pressure on liquid water, boiling takes place. (At 100°C the saturation pressure equals normal atmospheric pressure, hence that is the normal boiling point. On a mountain where the atmospheric pressure is 50 cm Hg the boiling point would be below 90°C.)

If the liquid water is drawn from the bottom of the vessel, so that saturated water vapor is left, a decrease in temperature causes some of the vapor to condense on minute dust particles, ions, etc., to form a fog. On the other hand, if the temperature is made to rise, the actual vapor pressure becomes farther and farther outdistanced by the increasing value of vapor pressure required for saturation.

The ideas just illustrated can be applied to the water vapor that is a part of our atmosphere. When the vapor is saturated, its *relative humidity* is said to be 100 per cent. Suppose that we con-

sider some air with water vapor at a pressure equal to half the saturation value, that is, with a relative humidity of 50 per cent. Then if the temperature is decreased regularly without allowing the volume to change, a decreasing amount of water vapor is required for saturation, so the relative humidity increases until finally it may reach the value 100 per cent. With further decrease in temperature, the relative humidity remains at 100 per cent and the excess water vapor condenses as fog or clouds. Thus, we can account for the simple statement that water condenses whenever a fixed volume of moisture-laden air is cooled sufficiently.

How Can Air Be Cooled? How is air ordinarily cooled to form fog, clouds, or eventually rain or snow? This can happen by two processes when air is in rising currents. First, the air receives less radiation[1] from the earth as the height increases. The other cooling effect is produced by the expansion of the air in the upward current as the pressure decreases. We shall have several occasions to recall that the sudden expansion of a gas produces a drop in temperature, and that compression produces a rise in temperature. A familiar example of the latter is the heating of a hand-operated football or tire pump when it is being used.

Air in a rising current, then, is cooled; so if the initial relative humidity is high, clouds may form at the altitude where the cooling is enough to produce condensation of some of the water vapor.[2] The so-called tropical rains are associated with the rising air currents "directly beneath" the sun, which we discussed earlier. After this air has much of the moisture removed from it, it flows northward or southward to descend again as part of the convection cycle illustrated in Fig. 288. This descending air mass is heated as the pressure upon it is increased, so its relative humidity becomes very low when it reaches the earth's surface. It is this very dry air which produces many of the world's great desert regions.

Ocean winds, such as those at the west coast of the United States, blow up the gradual slope of coastal mountains. In so doing, they rise and are cooled enough to lose much of their moisture to clouds and eventually to rain or snow. They then sweep down the eastern slopes of the mountain ranges as dry, desert-producing winds. This, in general, explains the greenness of the western

[1] See Chap. XVIII on radiation.

[2] The decrease of density of the rising water vapor, from expansion alone, opposes the saturating effect caused by the drop in temperature.

(a)

(b)

(*U.S. Weather Bureau.*)

Fig. 287. (a) Cumulus clouds of fair weather. (b) Low ragged clouds of bad weather (fracto-cumulus).

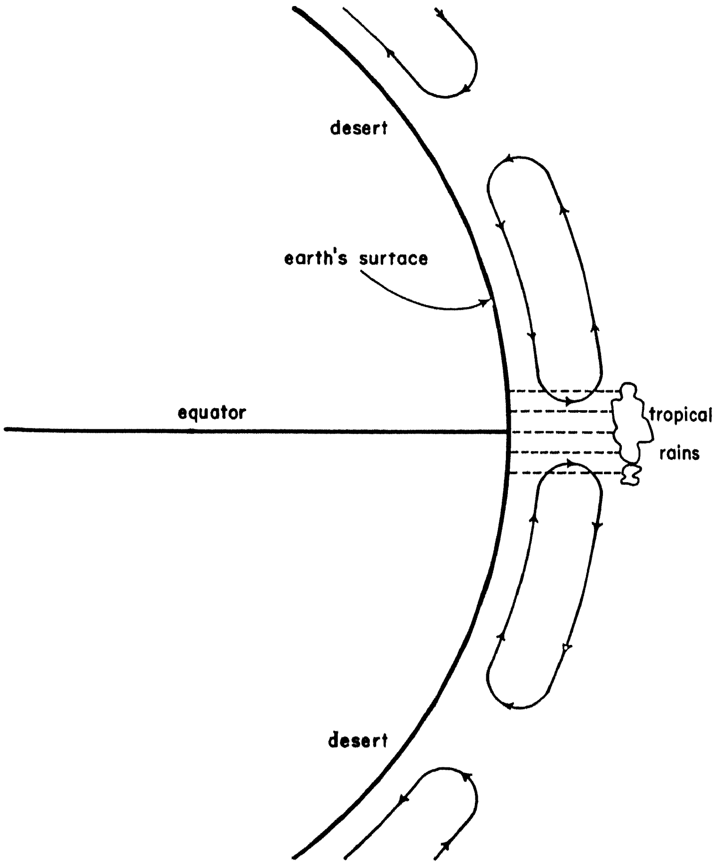


Fig. 288. Rising moist air leads to almost incessant rains at the Doldrums. The same air, dry and descending, produces deserts in the region of the Horse Latitudes.

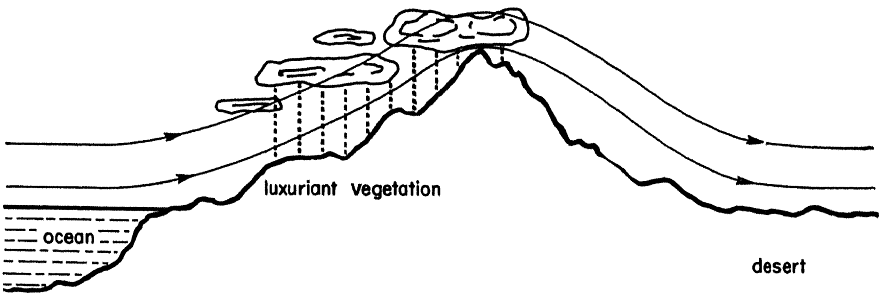


Fig. 289. Moist ocean winds give rise to much rain as they ascend mountain slopes. On the other side of the mountains, they descend as dry, desert-producing winds.

slopes of mountains on the Pacific coast and the dryness of the valleys on the eastern side.

Violent rising air currents, which are very local in character, always accompany the thunderstorms that are so prominent a part

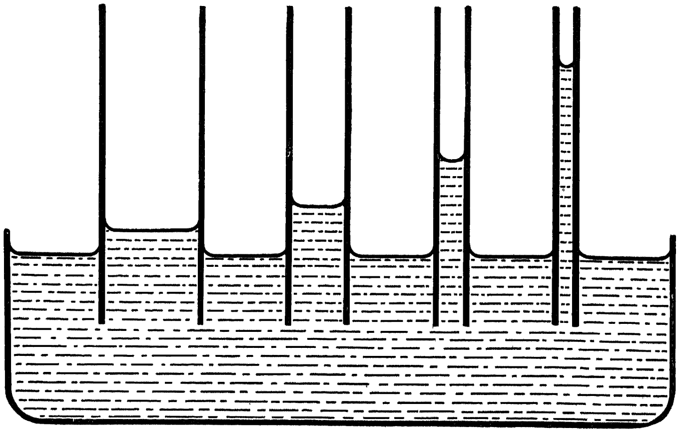
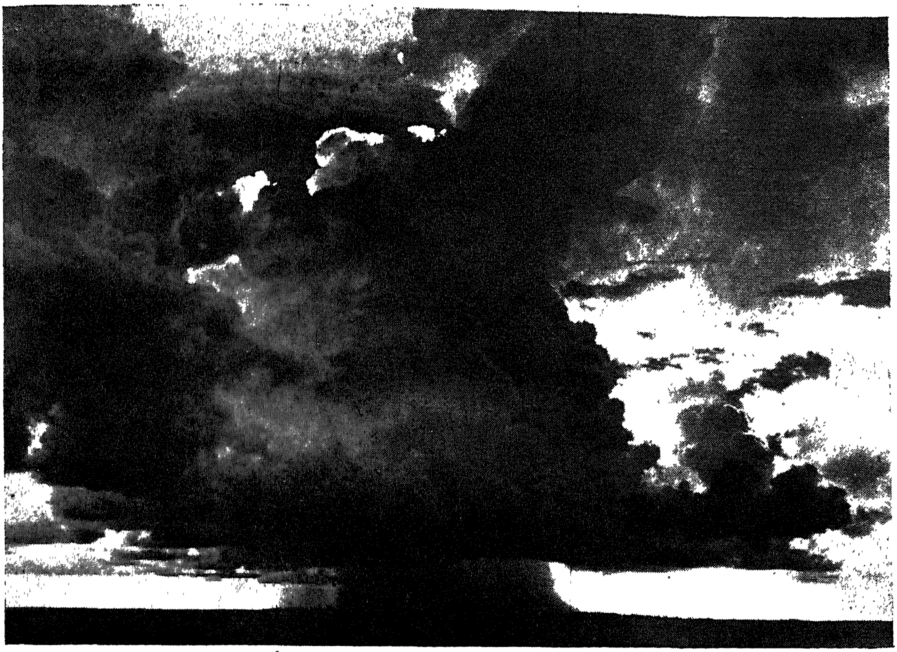


Fig. 290. Capillary action. The rise of the liquid is inversely proportional to the diameter of the tube. Liquid would not flow over the top of the smallest tube, for example, if it were half as long as illustrated. After the "horns" of the meniscus (concave form of the surface) would touch the top of the tube, further rise would reduce their length and decrease the upward capillary force until it would just balance the weight of the water column.

of our summer weather. In cyclonic storms, clouds and rain are to be expected when the warm southern winds are made to drop in temperature by contact with the cold air of the north. In general, any method of cooling moist air results in cloudy, and rainy or snowy, weather.

The Origin of Moisture in the Atmosphere. How does moisture get into the atmosphere? For the most part, the answer has to do with large bodies of water such as lakes or oceans. Undisturbed air immediately above the water contains saturated water vapor. Air currents then distribute this moisture to other parts of the atmosphere.

There is also continuous evaporation from plant foliage, and even "dry land" contributes to the water vapor of the atmosphere above it. Water evaporating from the surface of the soil is replaced by more which is raised from below by *capillary action.* We are familiar with the fact that water rises a certain distance in a glass



(*U.S. Weather Bureau.*)

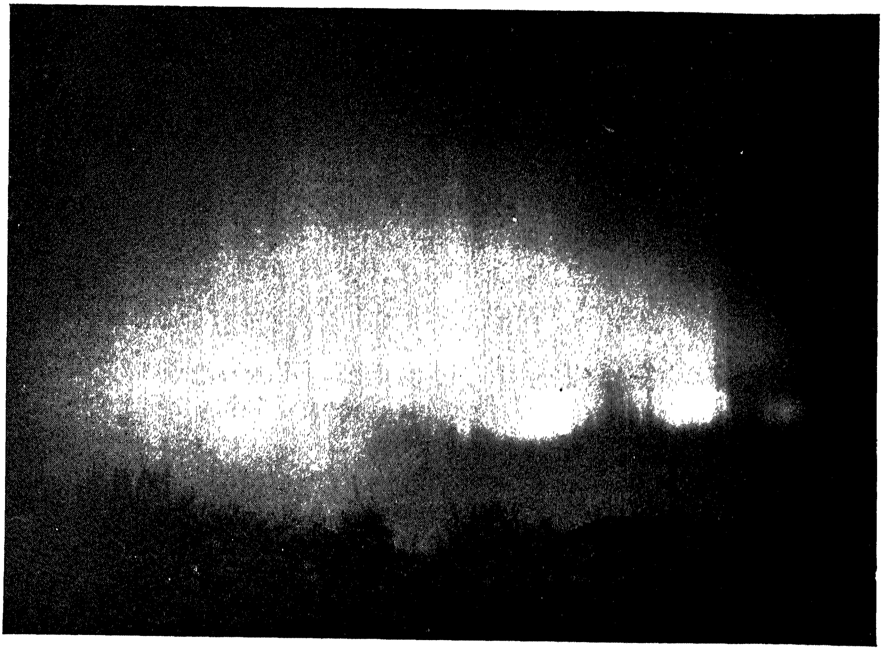
Fig. 291. Thunderheads.

tube of fine bore—the finer the hole, the higher the water rises. From the same effect, water rises in a towel if one corner dangles into a filled bathtub. These are examples of the effect of capillary action, which causes liquids to rise in fine channels or interstices when the forces holding the molecules of the liquid to those of the walls are greater than the attractive forces holding the liquid molecules together. This is the type of action that aids the evaporation of moisture from a considerable depth of soil.

Other Atmospheric Effects. We have confined our attention to some of the more general principles governing weather conditions. A complete discussion of weather and climate would include such things as the influences depending on location and extent of land and water bodies and on land topography, more detail as to the effects of the earth's rotation on wind direction, a review of the instruments to measure atmospheric quantities, typical cloud formations and the conditions under which they appear, the phenomena in the upper atmosphere, electrical and optical conditions of the atmosphere, and so on. A couple of examples of the

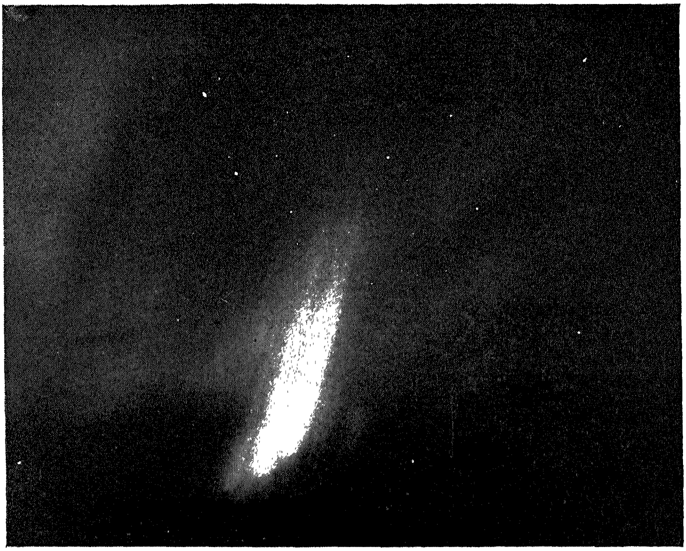
(*U.S. Weather Bureau.*)

Fig. 292. Lightning flash. Taken at Toronto, Canada.

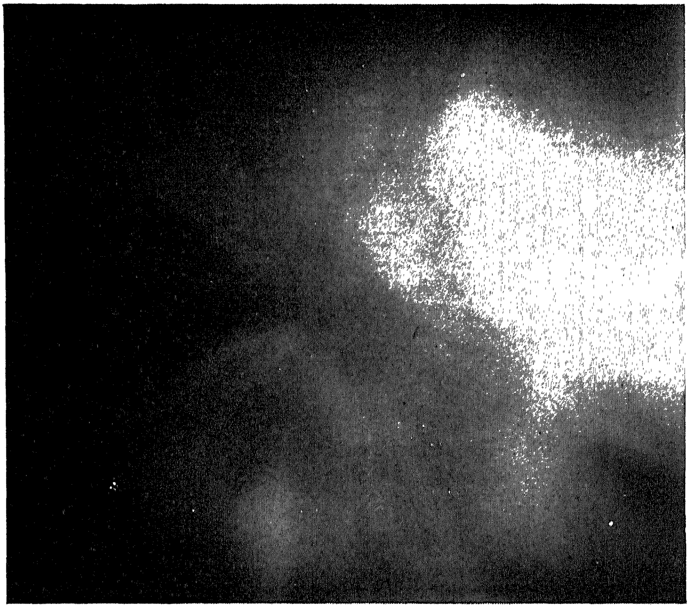


(*U.S. Weather Bureau.*)

Fig. 293. Aurora draperies, Oslo, Norway.



(a)



(b)

(*Photographs by C. W. Gartlein, Courtesy of National Geographic Society.*)

Fig. 294. Aurora. The rays are directed along the earth's magnetic field. The radial pattern of (b) is an effect of perspective.

latter type of disturbance will serve to show how varied are the influences associated with the weather.

Some of the more spectacular atmospheric effects are electrical in origin. Lightning, for example, is produced in thunderstorms,

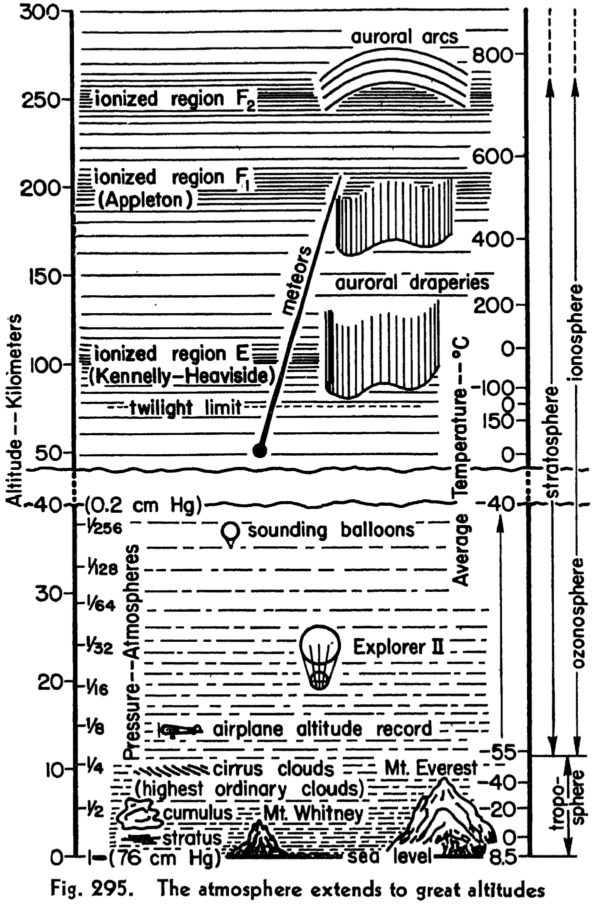


Fig. 295. The atmosphere extends to great altitudes with pronounced changes in character.

but the process is not understood in detail. The violent upward air currents and the clouds which accompany thunderstorms act as huge electrostatic generators, possibly because of the frictional effects on moving droplets or frozen drops. When the clouds are charged to a great enough potential difference with respect to one another or the ground to produce a breakdown, a huge spark, or lightning flash, is the result.

The aurora borealis of the northern hemisphere and the aurora australis of the southern hemisphere are also of electrical origin. They are simply huge electric discharges in the rarefied gases of the upper atmosphere. Except for extent, they are quite similar to the gaseous discharges in Geissler or Crookes tubes, described in Chap. XV. They appear to be related to sunspot activity. One theory considers the aurora to be caused by electrons shot off by the sun from sunspot localities; these electrons are forced by the earth's magnetic field to concentrate in the regions of the magnetic poles.

The United States Weather Bureau. We now have some idea of the working materials of organizations such as the United States Weather Bureau. This agency alone performs a service of almost inestimable value to farmers, to shippers, and to aviators in particular; in addition, it contributes something whose absence each one of us would feel. This service was made possible by the application of scientific methods to the study of the atmosphere.

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SUMMARY

Weather predictions depend on the scientific study of factors such as precipitation, wind velocities, barometric pressure, temperature, humidity, cloud types, and cloudiness. A weather map represents the values of some of these quantities over a region.

Many of the physical phenomena we have studied affect the weather. Wherever a part of the earth is heated above neighboring parts, rising currents of warm air set up ***convection*** currents in the atmosphere. Prevailing winds, shore breezes, etc., are the surface parts of convectional air currents. The steady currents in the

ocean, such as the Gulf Stream and Japanese Current, also are convectional. They have important influences on neighboring climates.

The earth's rotation modifies the direction of the prevailing winds, so that in the temperate zones cold air from the polar regions is deflected westward and warm winds from the tropics are deflected eastward. Where these warm and cold streams meet in the northern hemisphere, there sometimes forms a *cyclone,* consisting of winds blowing counterclockwise about a region of low atmospheric pressure, or an *anticyclone,* consisting of mild, clockwise winds about a high-pressure region. ***Hurricanes*** or ***typhoons*** are smaller, more destructive rotating storms. *Tornadoes* are very small, exceedingly violent whirlpools of air.

Relative humidity is the ratio of the actual pressure of water vapor in the atmosphere to the *saturation* vapor pressure. The saturation vapor pressure increases with temperature.

Rising air is cooled by expansion and by decreased radiation from the earth, so the relative humidity may increase and lead to clouds and rain or snow. Where convective air currents return to earth, they are very dry and, if continual, give rise to desert regions. Similarly, ocean winds are cooled as they blow up coastal mountain slopes, much of their moisture condenses, and they blow down the far side of the mountains as dry, desert-producing winds. Condensation also is produced by the violent rising currents of air in thunderstorms, and in cyclones where the warm air is cooled by contact with cold air currents.

Most of the atmospheric moisture is evaporated from large bodies of water, although some comes from foliage and from the soil with the help of *capillary action.*

There are many less general atmospheric effects, such as lightning and aurora.

The valuable services of groups such as the United States Weather Bureau are based on the principles we have reviewed.

QUESTIONS

1. What has Copernicus's idea of the seasons to do with weather?
2. What is the atmosphere?
3. How is atmospheric pressure measured? In what units may it be expressed?
4. What is a weather map? How are barometric pressures represented on it?
5. How do average temperature and barometric pressure change with increase in altitude?

6. In what way are ***convectional*** atmospheric currents set up? What is the general relationship between surface and high-altitude winds in such currents?
7. In what way would barometric pressures differ in different parts of a convectional circulation?
8. How do land and sea breezes arise?
9. How can ocean currents influence climate?
10. What does ***relative humidity*** mean?
11. What weight of water vapor is in an apartment room 20 ft long, 16 ft wide, and 10 ft high when the temperature is 85°F and the relative humidity is 100 per cent? When the relative humidity is 60 per cent? (At 85°F the density of saturated water vapor is 0.05 lb/yd^3.)
12. How can water vapor become ***saturated?***
13. Under what conditions may clouds be produced?
14. Where in a convectional current of air might you expect rain and where the driest air?
15. Why are valleys which are separated from the ocean by high mountain ranges frequently very dry?
16. What effect has the earth's rotation on prevailing wind directions?
17. What are ***cyclones? Anticyclones?*** How do they originate?
18. What are ***hurricanes? Tornadoes?***
19. How is lightning produced?
20. What is the ***aurora borealis? Aurora australis?***
21. Of what value is the work of the United States Weather Bureau?

CHAPTER XIV

INDUSTRY AND TRANSPORTATION

HOW DO WE USE ENERGY?

If every person in the United States left one hundred 60-watt lamps burning, the power used would just equal that now being taken from all the fuel and water-power sources in this country. The country's wholesale energy bill for one year is nearly ten

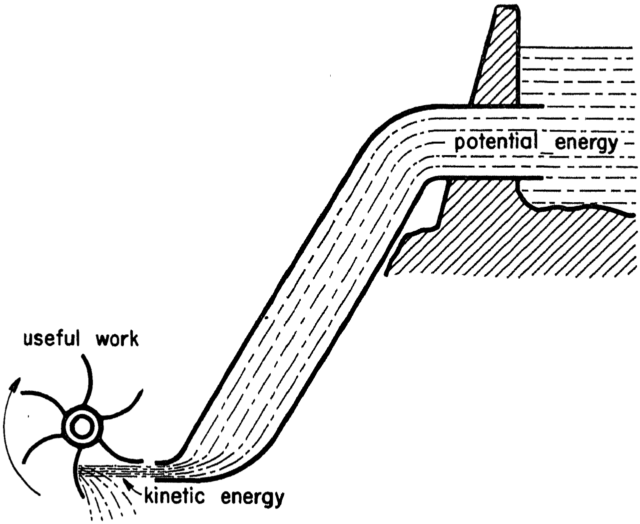
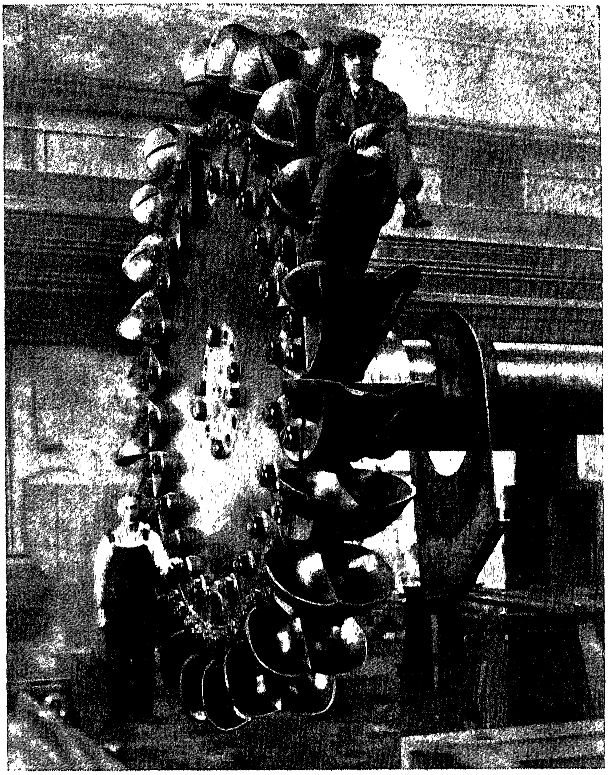


Fig. 296. The water wheel does useful work by virtue of the potential energy of water at a higher level which is converted to kinetic energy at a lower level.

billion dollars, a figure which for meaning needs comparison with defense appropriations or the national debt. This tremendous sum emphasizes the importance of power to each of us, and suggests that we ask what use is made of it.

All but about one-twentieth of the energy that we take is normally "lost" to further use, as it goes immediately into heat energy in industrial furnaces and in general heating equipment.

The remaining energy is applied by engines of various types to the operation of machinery, or it may be changed to electric energy for the operation of motors, for lighting, for heating, and for communications.

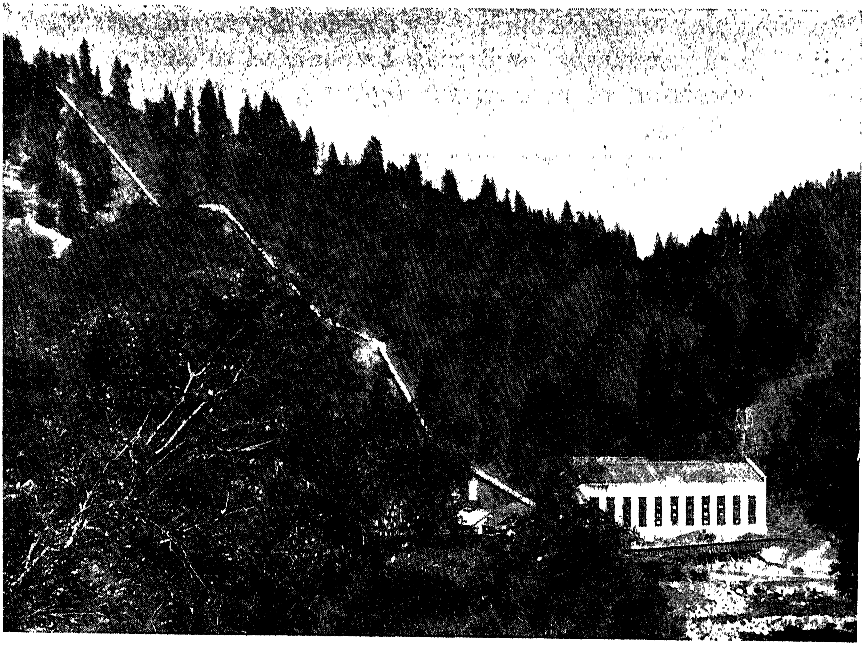


(*Allis-Chalmers Manufacturing Company.*)

Fig. 297. Pelton wheel for developing 56,000 HP at 250 rev/min. Operates by water from a 2,200-ft "head" at the Big Creek plant of the Southern California Edison Company.

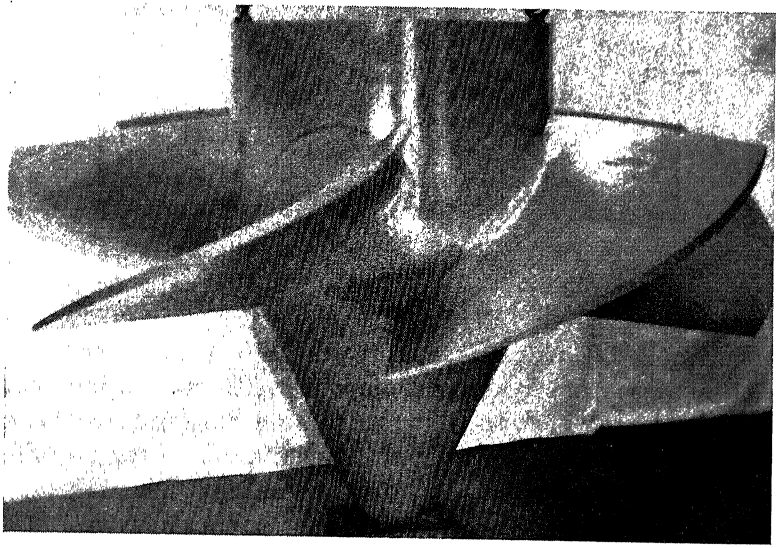
Water Wheels. Let us review the types of device that are used to take the energy from fuels and from water. The most primitive was the simple water wheel. Until recently, New England rivers turned the wheels that operated most of the hundreds of textile mills of this country. Although the water wheel now has difficulty in competing with other kinds of engine for applications of this sort, its modern descendants are gaining wider and wider use in hydroelectric plants where water power is converted into electric power.

Pelton Wheels. The ***Pelton,*** or ***impulse,*** type of wheel has been developed to operate large, comparatively low-speed electric



(*Power.*)

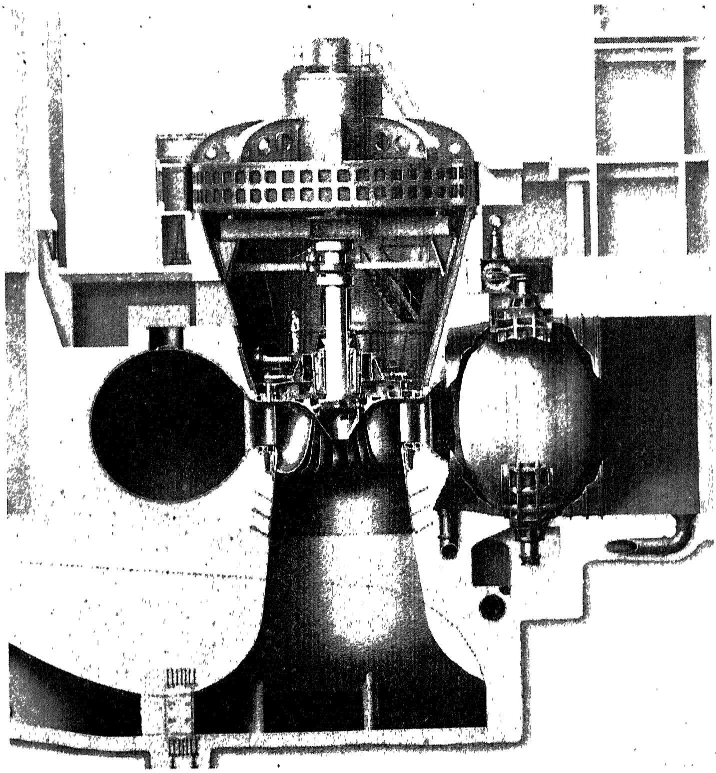
Fig. 298. High-head hydroelectric plant.



(*Power.*)

Fig. 299. Propellor turbine wheel with adjustable blades (102 in. diameter).

generators. Water from one or more nozzles streams at high speed against bowl-like attachments on the periphery of the wheel (Fig. 297), giving its kinetic energy to the wheel. Several Sierra Nevada power stations employ Pelton wheels operated by water



(*Allis-Chalmers Manufacturing Company.*)

Fig. 300. Cross section of one of the 54,000-HP water turbines at the Conowingo Project of the Susquehanna Power Company. This reaction wheel operates the vertical-shaft generator directly above it.

from huge pipe lines or penstocks which are 1,000 to 2,500 feet in height. One Swiss hydroelectric plant of this type takes its power from water which has a "head" of more than a mile!

Reaction Wheels. The ***reaction wheel,*** including the ***propeller type,*** has been developed in various modifications for different water flows and pressures (Fig. 299). In all cases, a large stream of water flows between blades on the wheel, turning it just as the wind rotates the fan of a windmill.

Hydroelectric Plants. Both Pelton and reaction-type wheels are made with either vertical or horizontal shafts. They are used

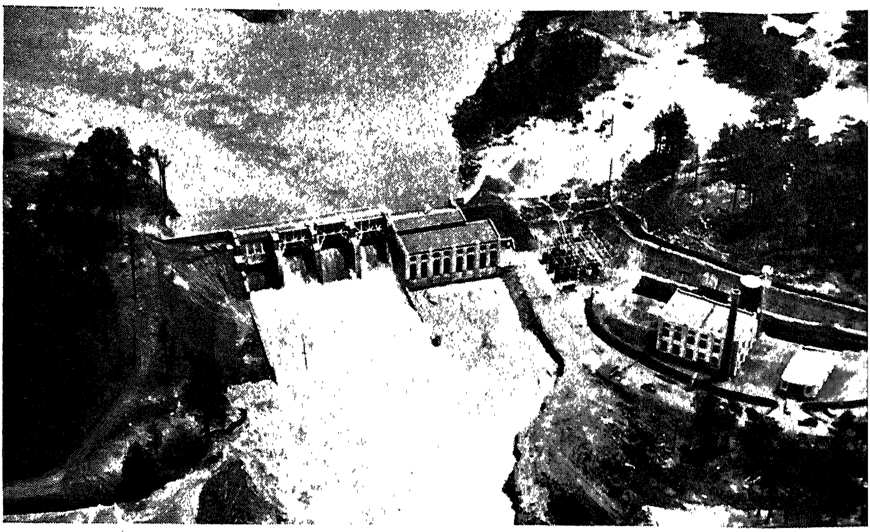


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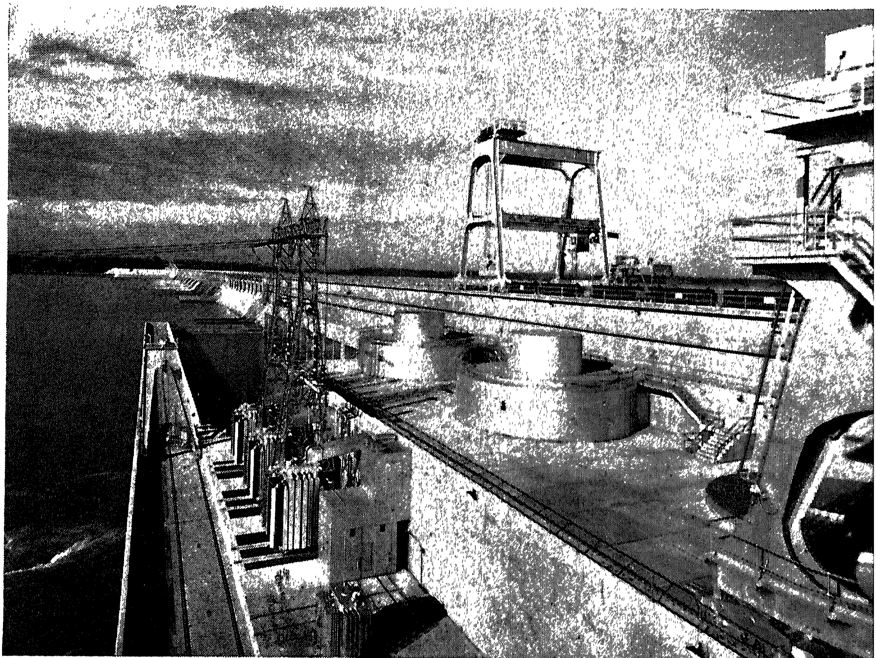
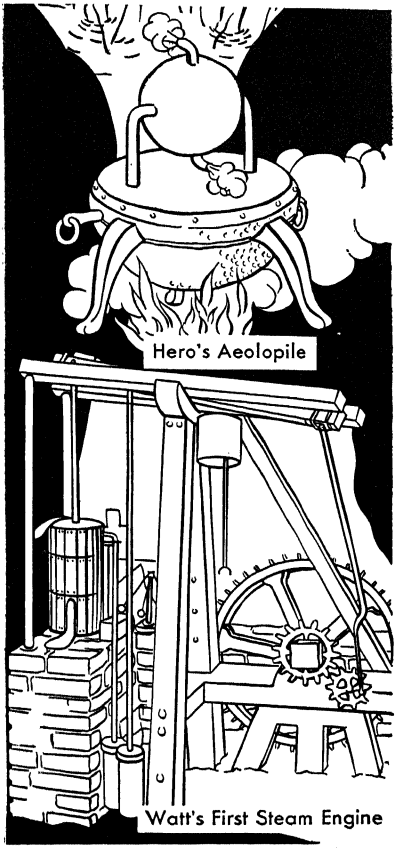
Fig. 301. Buzzard's Roost hydroelectric plant, Saluda River, South Carolina.



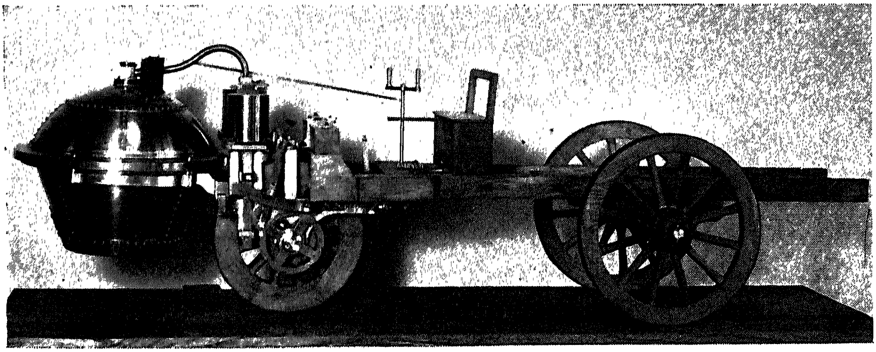
(Electrical World

Fig. 302. Wheeler Dam, one of the giant hydroelectric projects of the TVA, showin the "downstream" face and two 45,000-HP outdoor-type generating units. The navigatio lock is just visible across the water.



(*General Motors Company.*)

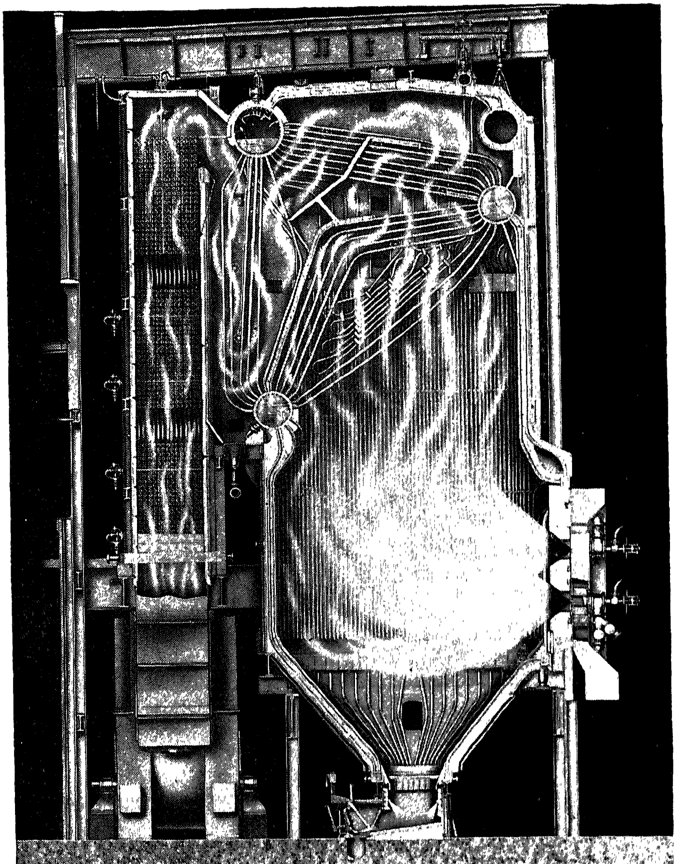
Fig. 303. Watt's first steam engine, and its ancient predecessor.



(*New York Museum of Science and Industry.*)

Fig. 304. Model of Cugnot's steam wagon. This first automobile was built in 1770.

almost exclusively to operate electric generators. Single hydroelectric units frequently have capacities of more than 100,000 kilowatts, and plants such as those at Boulder Dam and the Grand Coulee Dam may contain 20 or more of these large units.



(*Norris and Therkelsen, Heat Power.*)

Fig. 305. Modern boiler. Riley steam-generating unit, delivers 300,000 lb of steam per hour at 746 lb/in². Pulverized coal fired, water cooled.

HEAT ENGINES

Steam Engines. Until 1712, when Thomas Newcomen (1663–1729) constructed the first practical steam engine, water and wind had been virtually the only inanimate sources of mechanical power used by man. Newcomen's engine and an improved design by James Watt (1736–1819) were used chiefly for pumping water from

deep mines such as the tin and copper mines of Cornwall, although Watt finally succeeded in adapting his engine to a textile mill. Watt conceived a double-acting reciprocating steam engine which, unlike earlier types, was easily adaptable to rotating machinery,

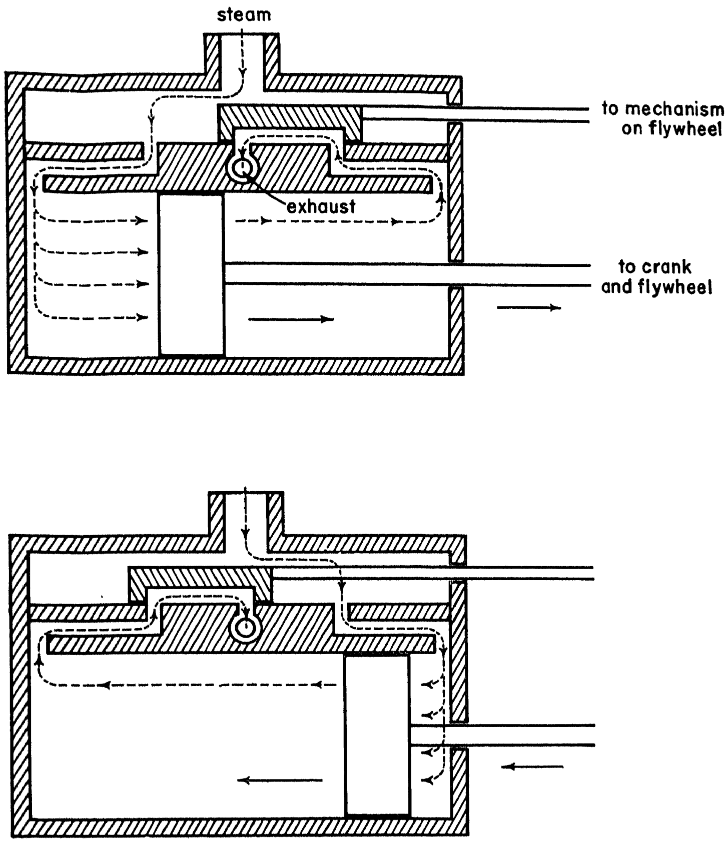


Fig. 306. Principle of reciprocating steam engine. The sliding valve in the upper compartment admits steam alternately to the two sides of the piston. It automatically opens the exhaust port to the opposite side of the piston.

but lack of proper machining methods delayed its realization until about 1800.

The Boiler. An important part of any steam engine is the *boiler* in which heat from burning fuel produces steam under a pressure greater than atmospheric. In large modern boilers the steam is formed and "superheated" to a high temperature and pressure in a great many tubes which almost fill the upper parts of the furnaces. These tubes have a very large total surface through

which heat can be absorbed. Many boilers of new types deliver steam at pressures up to 2,600 lb /in^2 (170 atmospheres) and temperatures up to 960°F (515°C)—literally "red hot" water vapor. This steam is capable of doing mechanical work when it is allowed to expand.

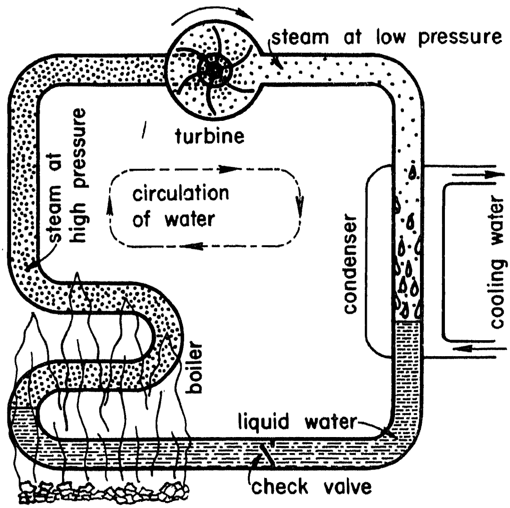


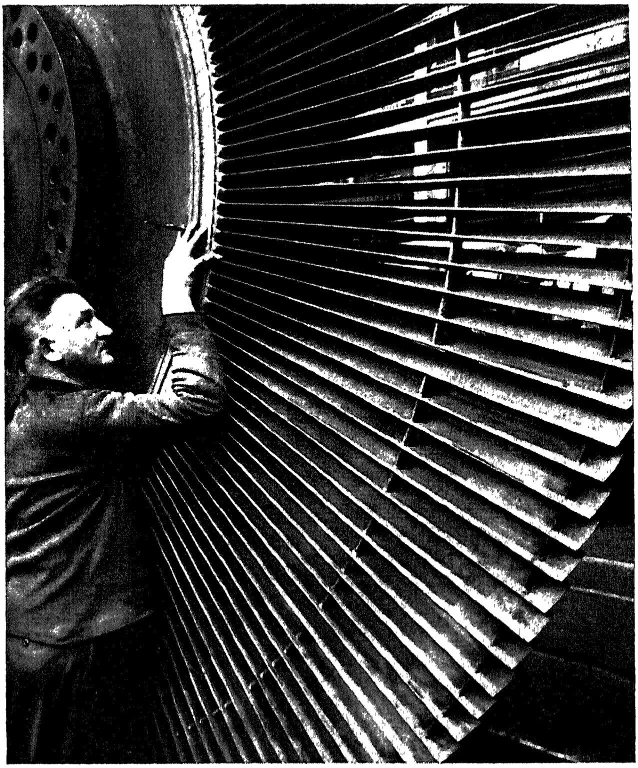
Fig. 307. Diagram of a steam plant.

The Ordinary Steam Engine. The *reciprocating steam engine* came into its own during the nineteenth century, when it found greatest use in mills, locomotives, and pumping systems. The method by which this type of engine takes mechanical energy from steam is shown in Fig. 306. Expanding steam forces the sliding piston back and forth. By means of a connecting rod and crank, this motion is made to rotate a shaft connected to the machinery to be operated. The simple crank, by the way, was protected by patents as late as Watt's day.

A typical steam plant has been represented in Fig. 307. It can be seen that the same water is circulated time after time, that is, through "cycle" after "cycle." In each cycle heat energy is added to the water, does work on a piston, and then is extracted in condensation.

The Steam Turbine. The modern *steam turbine,* developed at the turn of the last century, is rapidly replacing the reciprocating engine for large installations. The rotor of a steam turbine usually consists of a number of many-bladed fanlike wheels, mounted one

after the other on a single axle. High-pressure steam released against the faces of this rotor produces very rapid rotation, and in modern turbines the steam is redirected against successive sets of blades many times, until as much as possible of the available energy in the steam is extracted.

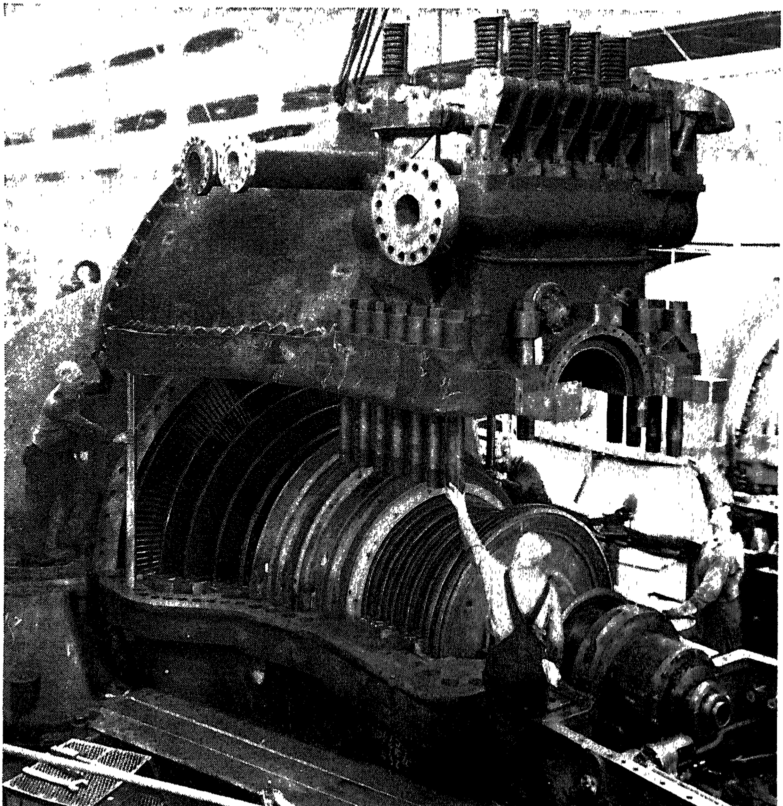


(*Westinghouse Electric and Manufacturing Company.*)

Fig. 308. Large rotor blade of 165,000-KW steam turbine. In operation the speed of the blade tips is 1,350 ft/sec, exceeding the speed of sound. The clearance between the outer edge of the blade and the housing is about $\frac{1}{100}$ in.

Steam-electric Units. Twenty or thirty years ago, turbines frequently were geared directly to mechanical devices. Now, however, especially where variable speeds are required, steam turbines often operate direct-current generators, which in turn feed electric motors that operate ship propellers or, indeed, locomotive drive wheels. Thus, with these turboelectric systems speeds may be changed continuously, simply by varying the voltages on the direct-current motors.

More than two-thirds of this country's electric power is derived from generators operated by steam engines—most of them turbines. Individual turbogenerators have been constructed for capacities as great as 160,000 kilowatts. Single steam-electric power stations may contain a number of large units.

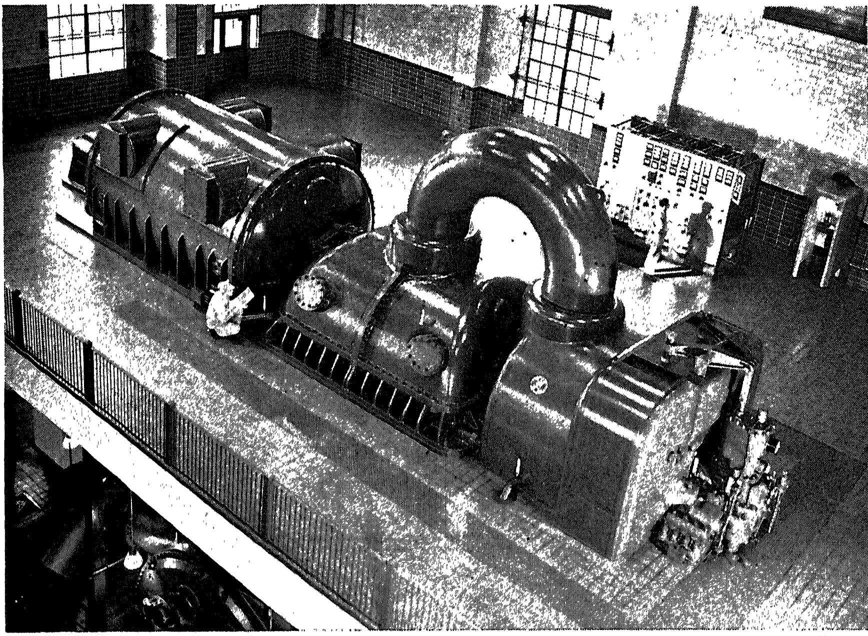


(*General Electric Company.*)

Fig. 309. 80,000-KW steam turbine being assembled for factory tests.

Internal Combustion Engines. The name "heat engines" includes, as well as steam reciprocating engines and turbines, ***internal combustion*** engines of the ***spark ignition*** and ***Diesel*** types, and also newly developed ***gas turbines.***

The Gasoline Engine. Commonly used in automobiles and airplanes is the ***four-stroke-cycle*** gasoline engine, more frequently called the "four-cycle" engine. In it, a spark ignites a mixture of



(*Power.*)

Fig. 310. 35,000-KW steam turbine and hydrogen-cooled generator (Westinghouse unit).

gasoline vapor and air. Expanding gases from the burning gasoline do work on a piston, which turns a crank and rotates a shaft connected to the driving mechanism. The operation of one cylinder of an engine of this type is represented in Fig. 311. Because one downward stroke of the piston is used to pump the fuel mixture into the cylinder, there can be a "working stroke" only once every two revolutions or four strokes. Hence the name "four-stroke cycle." This type of engine is seldom constructed to deliver more than 800 hp (600 kilowatts), except for airplanes, where 2,400-hp (1800-kilowatt) ratings have been reached.

The Diesel Engine. In Fig. 313 is illustrated an internal combustion engine in which there is a working stroke once every revolution. This is the ***two-stroke-cycle*** (or "two-cycle") engine. Because of a further modification, in that the fuel is sprayed or injected into the cylinder at a pressure so high that it ignites without a spark, the unit of Fig. 313 is called a ***Diesel*** engine. Fuel oils that are less highly refined than gasoline can be used

with comparative efficiency, so Diesel engines are becoming popular where moderately great power is required. They are

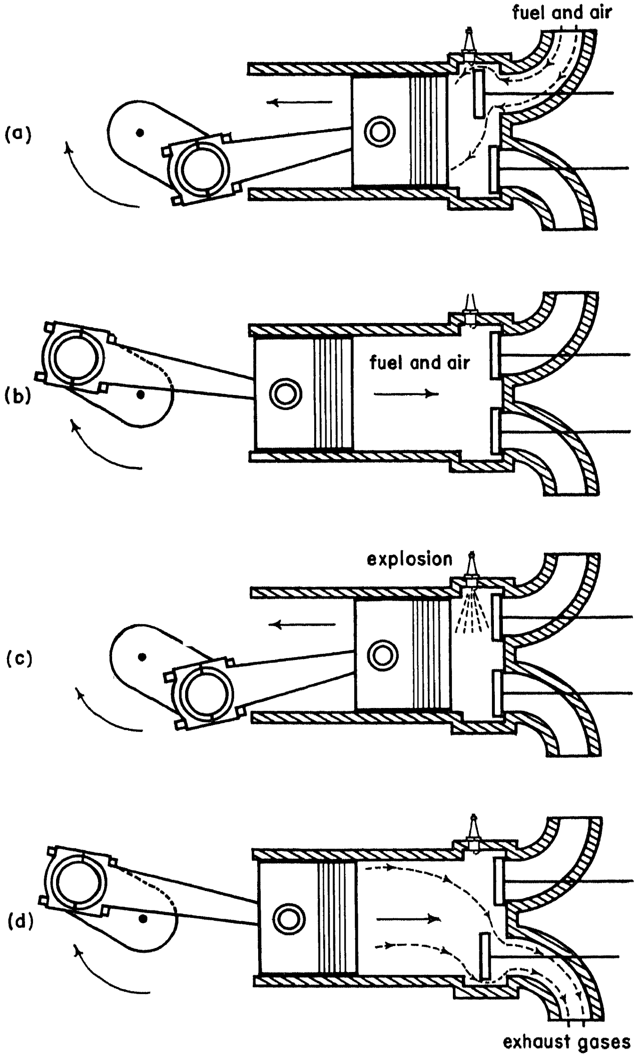
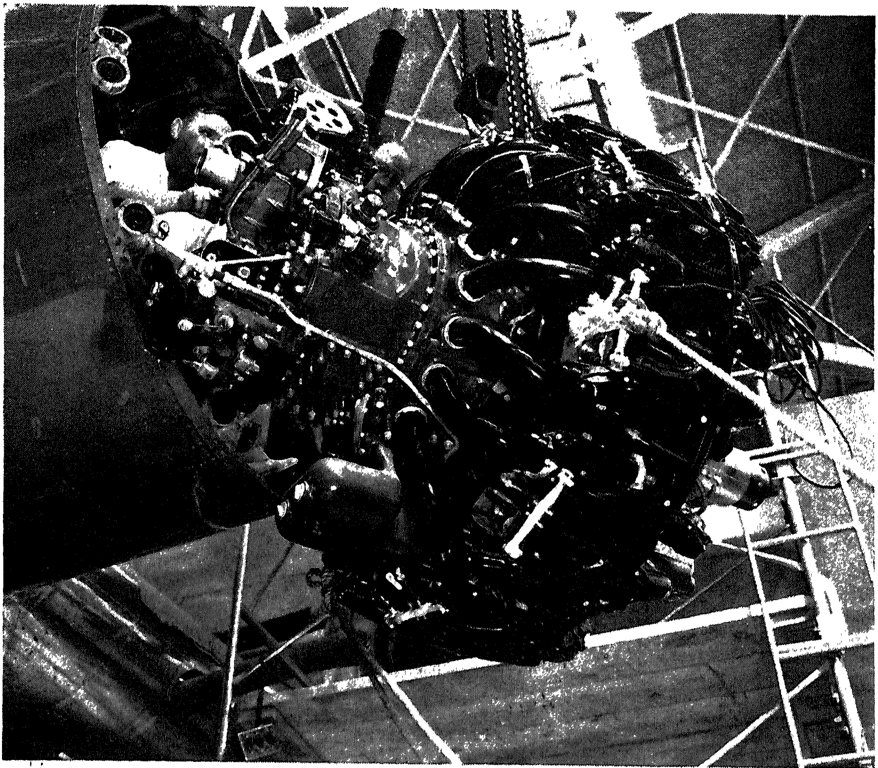


Fig. 311. Four-stroke cycle for a gasoline engine with spark ignition. Fuel and air are sucked in during the first stroke (a), compressed during the second stroke (b), and fired during the third stroke (c). The gaseous products of combustion are exhausted during the fourth stroke (d). There is only one working stroke (c), revolution being maintained during the other strokes by other pistons working on the same crankshaft and by a fly wheel.

employed particularly in trucks and to operate electric generators of medium output—up to about 4,000 kilowatts. Diesel-electric



(*Aviation.*)

Fig. 312. Mounting a 2,000-HP Wright Duplex Cyclone aircraft engine.

drives are installed in many of the new lightweight locomotives and in numerous ships of medium tonnage. There is even a fleet of suburban buses, each of which is powered by an "All-service." Diesel-electric unit. The electric energy may be taken either from a Diesel-driven generator or directly from trolley wires over streets where trolley cars formerly ran.

Excellent claims are made for Diesel-electric locomotives, not only for passenger service, but also for freight hauls. They demand almost no time out for servicing as compared with about 50 per cent availability for ordinary steam locomotives. Moreover, they require no water stops and need only one-seventh the usual number of fuel stops. These factors have made it possible to cut certain fast freight schedules almost by half, so that they nearly rival the times for passenger runs.

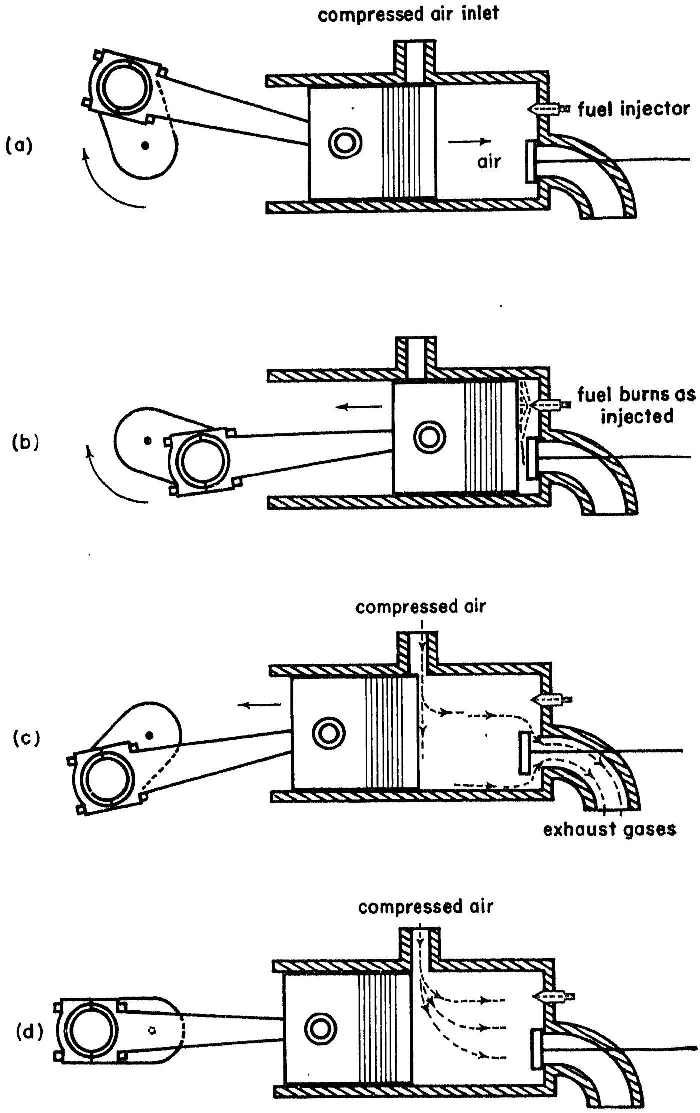
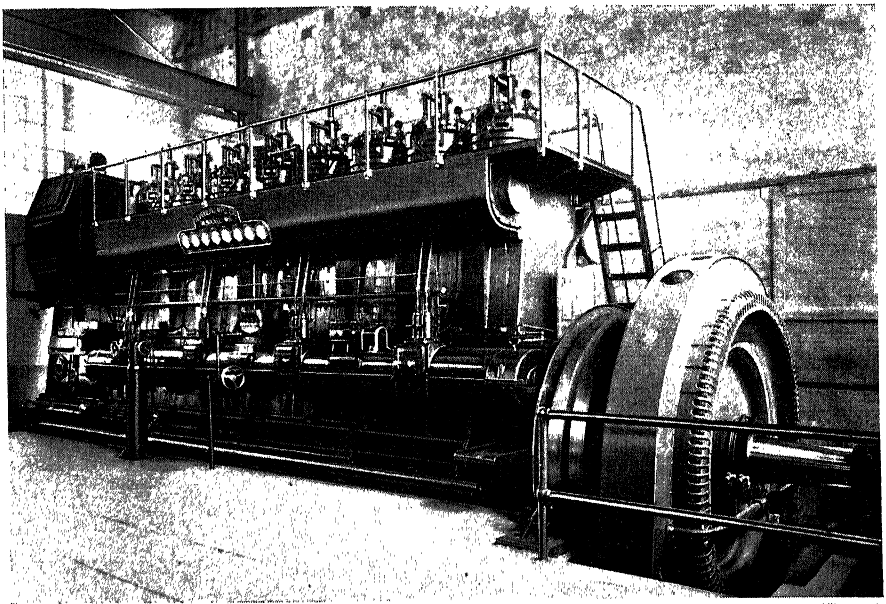
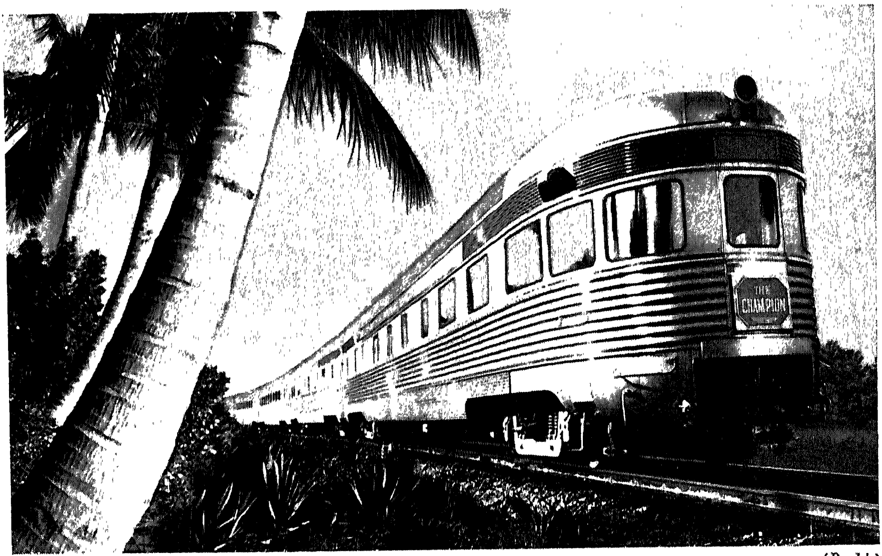


Fig. 313. Two-stroke cycle for Diesel engine. The intake stroke of the "four-cycle" engine is eliminated by injecting fuel under pressure (b) and the exhaust stroke by removing unwanted gases with a blast of compressed air (c). The Diesel principle, ignition of fuel by high compression of the air into which it is injected, may be used with the four-stroke cycle. Also, a two-stroke cycle can be operated by spark ignition of gasoline.



(*Power.*)

Fig. 314. Diesel-driven AC generator.



(*Budd.*)

Fig. 315. Diesel-electric train of lightweight stainless-steel construction.

A further point in favor of an electrically driven locomotive is that there is the chance to avoid worrisome braking problems such as the excessive wear of brake shoes and wheels in bringing a heavy train down a mountain grade. So-called "dynamic braking" is employed, that is, the motors connected to the wheels are made to operate as generators, so that the mechanical energy of the rolling train is changed to electric energy and then dissipated in a resistance. This accomplishes in an extra step just what ordinary brakes do directly, but without overheating any mechanical parts.

The Gas Turbine. Envisaged long ago were turbine-type internal combustion engines, which would substitute smooth rotary motion for the to-and-fro motion of pistons. Many unforeseen difficulties had to be overcome, but recently large turbines driven by gases flowing continuously from burning fuels have at last proved satisfactory.

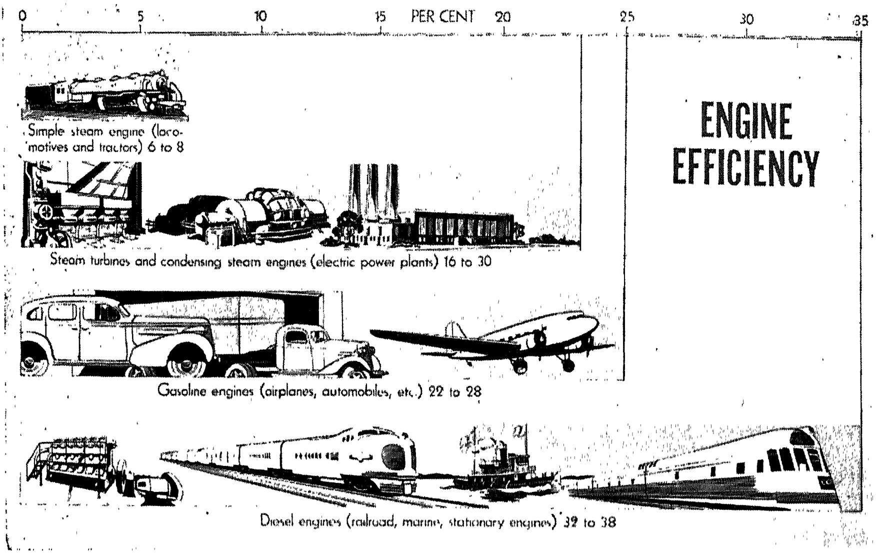
Efficiencies of Heat Engines. By efficiency of a heat engine, we mean the fraction of the heat content of the fuel that is converted to useful mechanical energy. Perhaps it is not surprising that this efficiency never approaches 100 per cent. In the first place, the fuels frequently are not burned completely, so a certain amount of their energy content is wasted immediately. The moving parts of the engine do work against frictional forces; this part of the energy "loss" is considerably greater in reciprocating engines than in properly constructed turbines. Furthermore, heat energy is removed from the engine by radiation and by conduction to the cooling water and surroundings.

Even if all the heat "losses" we have mentioned were eliminated, there still would not be complete conversion of heat energy to mechanical energy. In heat engines, expanding steam or combustion gases lose heat energy when they do mechanical work, and their temperature drops. If all their heat energy were to be converted to mechanical energy, their temperature would have to drop to absolute zero. Obviously this does not happen; so heat energy is lost in the exhaust gases. It turns out that the efficiency of a perfect heat engine in which the initial gas temperature is T_1°K and the exhaust gas temperature is T_0°K would be

$$\text{Efficiency} = \frac{T_1 - T_0}{T_1}$$

We see that the efficiency can be 100 per cent only if $T_0 = 0°K$.

Actual efficiencies of reciprocating steam engines and steam turbines (including boilers) range from 6 per cent up to about 30 per



(*General Motors.*)

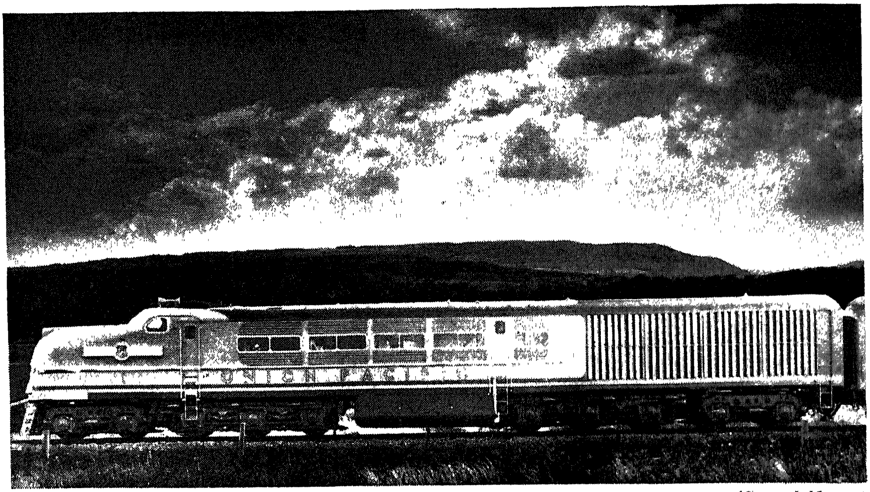
Fig. 316. Efficiencies of heat engines.

cent. The efficiencies of gasoline engines for automobiles and airplanes extend to between 20 and 30 per cent, and Diesel engines have a maximum of about 38 per cent.

An interesting, though at present economically impracticable, steam turbine has been constructed to operate between the surface temperature of warm tropical seas and the lower temperatures found at some depth. To obtain steam at the higher temperature, it was necessary to have an operating pressure somewhat below atmospheric pressure. If our supply of fuels should eventually become exhausted, it is possible that we may find use for this type of turbine—as well as for solar engines operating directly from the sun's rays and tidal power plants. We might even witness a renaissance of the windmill!

POWER IN INDUSTRY

We see that there is great variety in the type of power installation which might be chosen for an industrial plant. Of course, the



(General Motors.)

Fig. 317. Steam-electric locomotive.

unit decided upon is that which will do the desired work most cheaply. This involves a great many questions such as the following: What types of power are most readily available? Do the power requirements warrant special electric generating equipment? If so, what space is available for this equipment? Is there ample fresh water for boilers? Can fuel be brought in by ship or pipe line? Which type of installation would have the best balance between initial cost, operating expense, and the salary of additional employees?

Obviously, the answers to these and many other similar questions will be different for different plants, and even for the same plant at different times. In the latter case, where the advantage shifts from one type of unit to another, there may be duplicate installations. For example, numerous power stations are arranged so that they may be operated by Diesel engines when the cost of Diesel fuel oil is low as compared with coal and by steam turbines when the reverse is true. Similarly, some generating stations use hydroelectric generators during seasons in which water is plentiful, and steam-electric or Diesel-electric at other times.

The same sort of decision must be made as to the powering of trains, ships, and airplanes and even trucks, buses, and tractors, the latter group especially when entire fleets are to be considered. Again, for example, the variety of answers is shown by the different types of locomotives now used on major lines in the United States:

coal or oil-burning steam engines, simple electric, Diesel-electric, and steam-electric.

Electricity and Machines. Machines in industry range from typewriters and other business machines, through looms and cotton pickers, to the rolls of steel and glass mills, conveying systems, and giant presses. They have become so complex and so specialized that a good-sized library could be filled with the patent claims which cover them. One of the few important generalizations which may be made about these machines is that a greater and greater fraction of them are being operated electrically. The electric power produced in this country, almost 40 million kilowatts in central power stations, is twice the value generated only 15 years ago, and it is now increasing at an even greater rate.

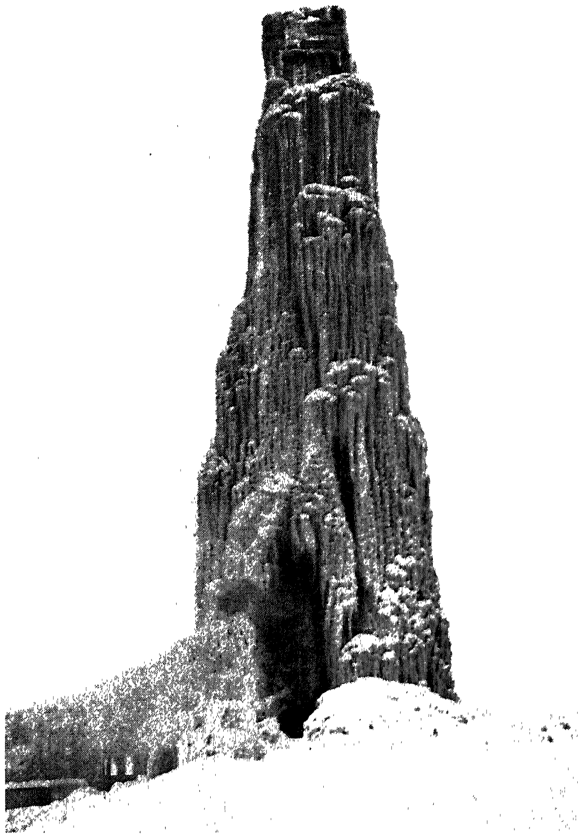
Urbanites, especially dwellers of New York City, become alarmed at the thought of an elevator operators' strike. If, however, ***electric power*** goes on strike, not only do elevators stop, but subway passengers are trapped underground, street cars halt, we modern cave dwellers would be without the light upon which we so depend, our water no longer would be pumped up to us, our furnaces with electrically operated fuel feeds would stop supplying heat, accounting machines and even most cash registers would be silent, and sewage would accumulate at disposal plants. To satisfy our curiosity or register a complaint about these conditions we might reach for a telephone—but even that would be perfectly dead. Without electricity a modern city would become uninhabitable.

PUMPING HEAT

In this age we have summer foods during the winter, much of our food is brought to us from great distances, we expect ice cream and cold drinks, our buildings, trains, and buses are air conditioned, and we take refrigerators for granted as readily as bathtubs. These things are made possible by heat pumps, more commonly known as refrigeration systems.

How Do Refrigerators Work? All refrigeration machines or ice-making plants operate about the same way. The working material, usually ammonia (NH_3), sulfur dioxide (SO_2), methyl chloride (CH_3Cl), or Freon (CCl_2F_2), is circulated in a closed system. Briefly,

this material absorbs heat from the part of the system that is to be cooled, and carries this heat to a radiator or water jacket where it is given up. Then the material is circulated back to the cooling compartment to absorb more heat.



(*Copyright Brown Photos.*)

Fig. 318. Ice gusher near Big Piney, Wyoming—not a winter scene. The expansion of escaping gas froze water, which was forced out with it. This natural refrigerator continued to spout ice for almost two months before the well could be capped.

But how can heat be absorbed from a place that already is colder than its surroundings? This can be accomplished by making a liquid evaporate at that place. The liquid working material will evaporate if forced under pressure through a jet into a chamber where the pressure is low. Each kilogram of the evaporating liquid absorbs an amount of heat equal to its heat of vaporization, so it

cools whatever surrounds it. The vapor then moves on to a pump which compresses it into a hot liquid. The liquid is cooled in a radiator or water jacket and again is circulated through the evaporation jet, where it starts its cycle once more. For efficient

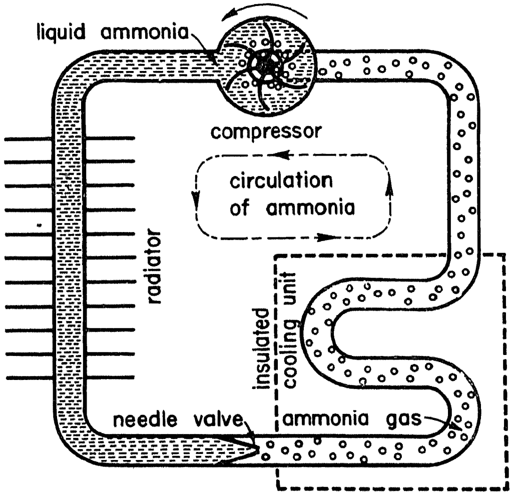


Fig. 319. Principle of a refrigeration system. (Compare with Fig. 307.)

performance, it is important to have the cooling compartment surrounded by heat-insulating material.

The refrigeration system diagrammed in Fig. 319 appears to be very similar to the essentials of a steam plant shown in Fig. 307. The refrigerating material goes through cycle after cycle, just as water does in a steam plant, except that every operation is reversed—where heat is *added* in the steam cycle, heat is *removed* in the refrigerator; where work is done *by* the steam, work is done by a pump *on* the refrigerating material, and so forth.

The Gas Refrigerator. The Electrolux refrigerator uses an ingenious modification of the above process. Instead of depending upon a mechanical pump, convective circulation is maintained by a small flame. Ammonia is the refrigerating material, but water and hydrogen also are circulated in parts of the system. Although the entire process described in Fig. 320 may appear complex, its essential parts are simple. Ammonia gas, evaporated from a water solution by heat from the flame, passes through the radiator and condenses into a little reservoir. An outlet from the reservoir leads into a tube filled with hydrogen. Ammonia evaporating into the

hydrogen increases the density there so that the mixture falls and is replaced by the lighter pure hydrogen rising in another tube. Because the gaseous ammonia is continually carried away by the hydrogen, evaporation from the ammonia reservoir continues, and

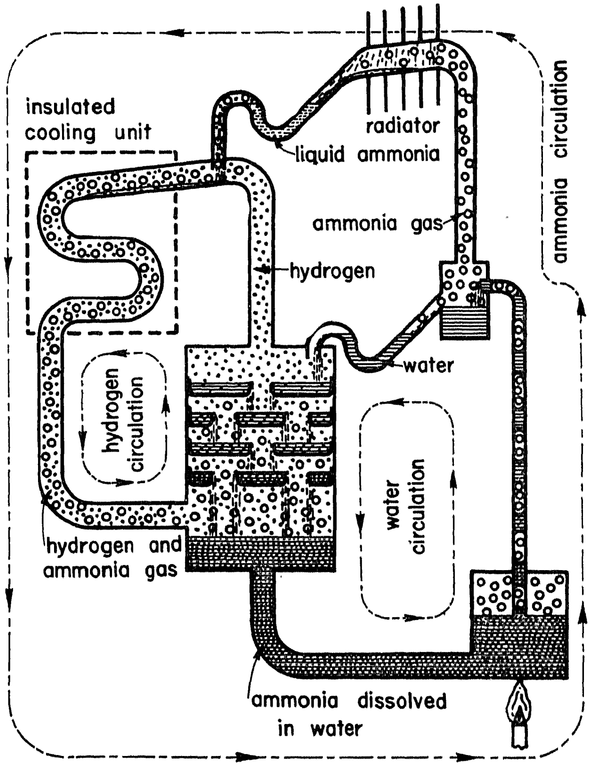


Fig. 320. Principle of Electrolux gas refrigerator. Circulation of ammonia is maintained by convection instead of by a pump as in the ordinary refrigeration system. Liquid ammonia evaporates continually without use of an expansion valve because its vapor is constantly swept away by a stream of hydrogen (upper left).

cooling takes place in that region. The ammonia-hydrogen mixture is bubbled into water which absorbs the ammonia and leaves the hydrogen free to rise again to the cooling chamber. The ammonia solution then flows above the flame, where the ammonia evaporates and rises again to be cooled and condensed in the reservoir.

A Refrigerator Is a Heat Pump. A clever housewife might get the idea of cooling her kitchen by leaving the refrigerator door open during the hotter summer weather. But would the kitchen really be cooled? The energy put into the refrigerator, whether as electricity

or in gas to feed a flame, all is transformed into additional heat energy. Therefore, once the accumulated ice had been melted, our housewife's kitchen would be heated rather than cooled. This emphasizes the fact that a refrigerator cools, not by changing heat

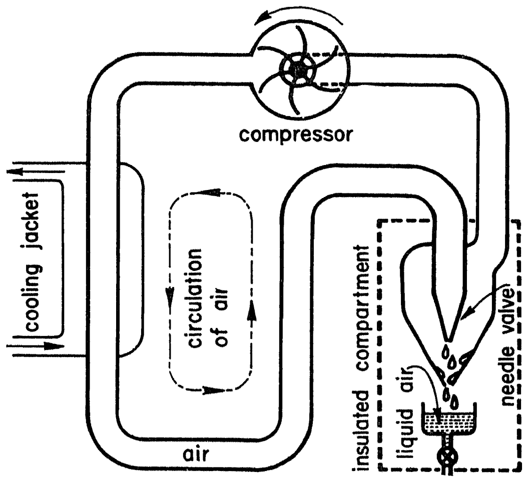


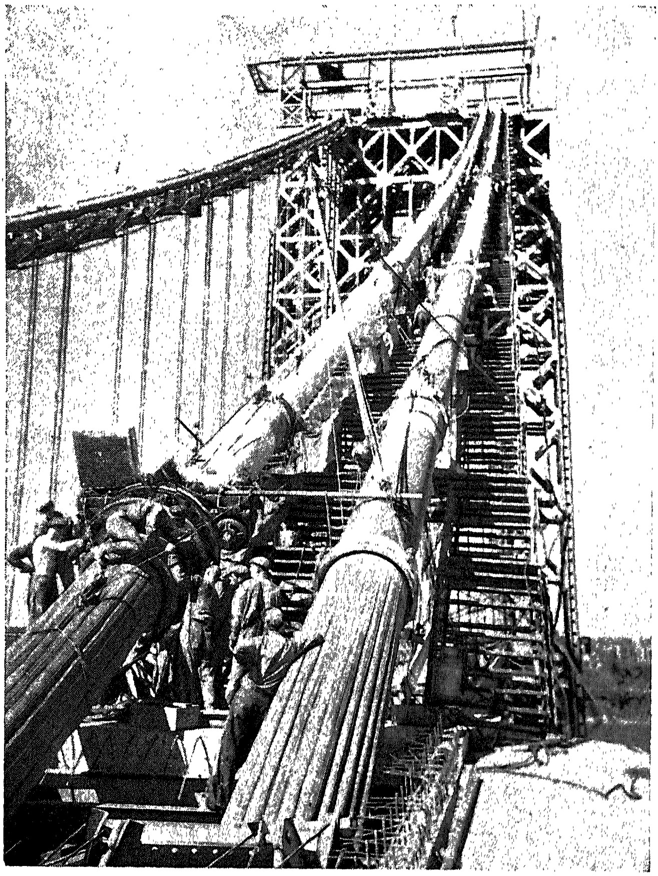
Fig. 321. System for liquefying air or other gases. This is essentially the same as an ordinary refrigeration cycle with needle valve arranged to facilitate collection of the liquid.

energy to some other form, but by "pumping" heat energy from one place to another. Energy is required to do the pumping; so the heat energy lost in one spot is more than compensated by heat gained elsewhere (efficiency is ***always*** less than 100 per cent).

Air Conditioning. Let us carry our kitchen-cooling attempt a little further, and place the radiator outdoors or else replace the radiator by a jacket through which cold water flows (as is done in large refrigeration plants). Then, indeed, heat is pumped out of the kitchen to the outdoors or else down the drain in a stream of water. This would be a simple air-conditioning system. A more extensive cooling system for a building would differ not only in size, but in having ventilating ducts and fans to provide proper air circulation throughout the building.

One large electrical company has equipped a California building with an air-conditioning unit which pumps heat from the building into a stream of water during the summer, but pumps heat in the reverse direction during the winter. This is of considerable advan-

tage as a heating unit, because each kilowatt-hour of energy supplied can pump about four kilowatt-hours of heat energy from the water into the building. So, for heating purposes, each unit of energy is multiplied fivefold. It should be remarked that this is no



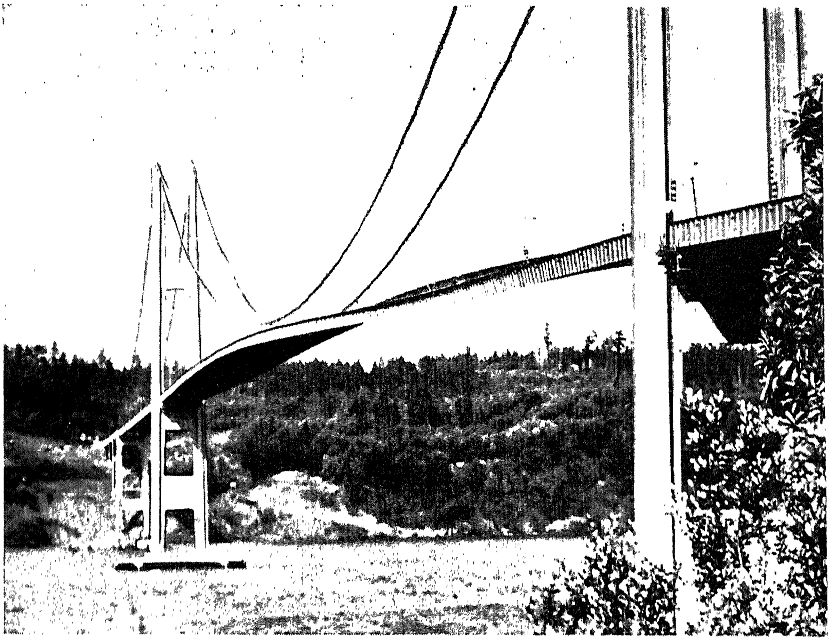
(Roebling.)

Fig. 322. Wrapping the cables of the George Washington suspension bridge.

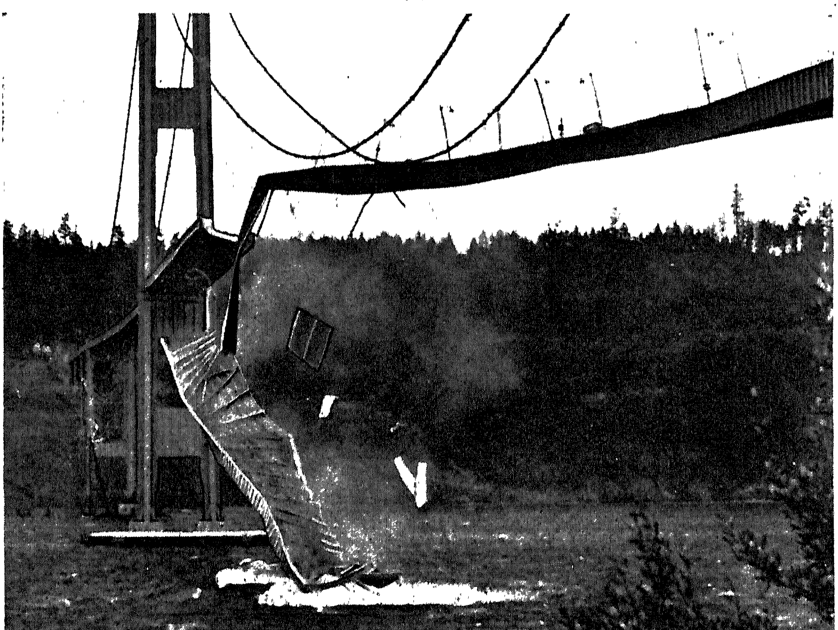
more a violation of the law of conservation of energy than is the possibility of using only 10 gallons of gasoline in a truck that hauls a 1,000-gallon tank of gasoline from one city to another.

SOME WORRIES OF ENGINEERS

General Construction. We have learned something of the part taken by the metallurgist and the structural designer in increasing the



(a)



(b)

(*Wide World.*)

Fig. 323. Tacoma Narrows Bridge failure. (a) Large undulations set up by wind; (b) \$6,500,000 suspension bridge plunges 200 ft to water.

strength of modern machines while reducing their weight. These men have made possible many of the advances in design of airplanes and fast trains. Equally vital have been their contributions to the development of high-speed machinery, such as the whirling blades of steam turbines, which at their outer edges sometimes travel as fast as a rifle bullet! At these terrific speeds, delicate balance is required to prevent disastrous vibrations. Frequently, structures that are well able to stand occasional shocks will fail when similar shocks are repeated regularly as from vibrations.

Even in so-called stationary structures, such as buildings, bridges, tunnels, and dams, the engineer finds new problems or discovers new solutions to old problems. The noise of the rivet hammer, formerly so characteristic of the rising steel framework of a building, has in a number of cases been absent. This is just one example of the general trend away from riveting and toward increasing strength by welding. Skyscrapers and large dams, which depend upon generations of use to justify their initial cost, must be able to withstand earthquake shocks; suspension bridges and buildings must resist the forces of high winds; new bridges are called upon to support more and more severe vehicle loads on ever-longer spans. Again the possibility of vibration must not be overlooked.

One of the most vivid examples of the destructive effect of vibrations was the failure of the Tacoma Narrows Suspension Bridge in November, 1940. Heralded during its July, 1940, opening as the world's most graceful bridge and with the third longest span in existence, this $6,500,000 structure was transformed by vibrations caused by wind energy into the ugly mess shown in Fig. 323.

AIR TRANSPORT

Fluid Flow. The field of aeronautical engineering has a great many very special requirements. The scientific basis of high-speed flight was laid many years ago when the physicist Bernoulli discovered an important property of fluid streams. Almost contrary to what one might expect intuitively, the pressure in a rapidly moving fluid *decreases* as the speed *increases*. If a compressed air stream is sent downward through a hole in a disk (Fig. 324), and a second disk is brought up from below, the lower disk is not blown away, but is actually attracted strongly into the moving air stream and held near the upper plate. Twenty-five

pounds may easily be supported on a disk of 5 in. diameter! The air pressure in the rapidly moving air stream between the plates is reduced well below normal atmospheric pressure, so the atmospheric pressure upward on the lower plate gives a considerable resultant "lift."

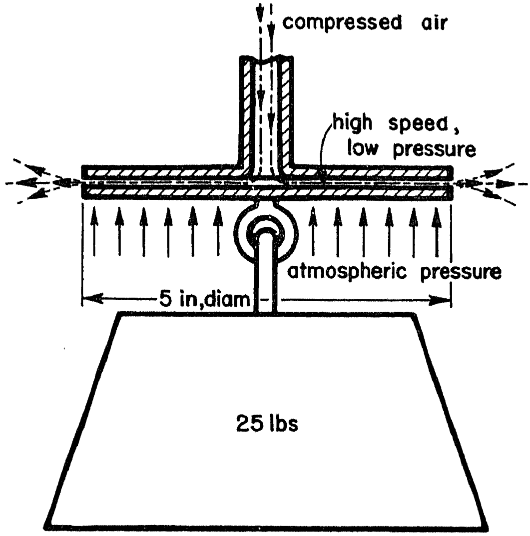


Fig. 324. Demonstration of Bernoulli's discovery that pressure is decreased in a region of increased fluid speed. Air, entering from above, passes between the plates at very high speed. The large supported weight is evidence of decreased pressure between the two plates.

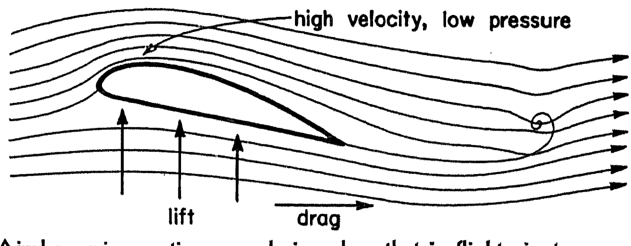
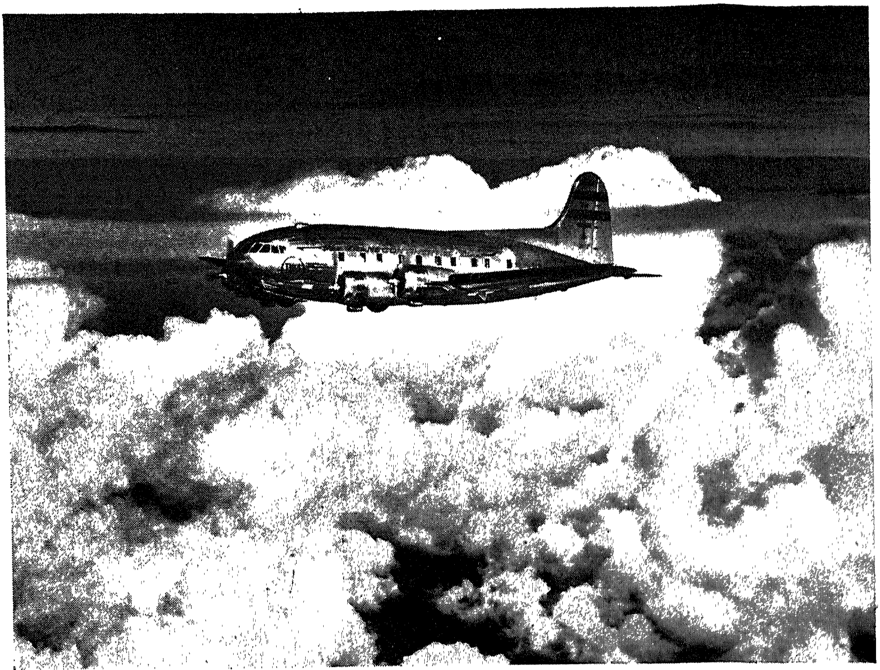


Fig. 325. Airplane wing sections are designed so that in flight air streams past the upper surface at a greater speed than that past the lower surface. This sets up a region of reduced pressure above the wing (according to Bernoulli) so that the greater pressure below can produce a lift. Eddies, one of which is shown behind the wing, approach nearer to the trailing edge if the wing is tilted further. At extreme angles they may creep over the top of the wing, reduce the lift, and help send the plane into a "stall."

Airplane Flight. The first successful power-driven airplane flight by the Wright Brothers in 1903 at Kitty Hawk, North Carolina, climaxed a long series of experiments by many workers in attempts to achieve "lift" and "control" with wing surfaces.



(*Transcontinental and Western Air.*)

Fig. 326. Boeing Stratoliner. Has sealed cabin maintained at increased pressure to permit operation at higher altitudes.

A typical modern wing section or "airfoil" is represented in Fig. 325, with the airflow "stream lines" indicated. The air flowing along the upper surface must have a higher velocity than that along the lower surface to maintain the flow lines shown.[1] Therefore, from Bernoulli's principle, the pressure is reduced on the upper surface and there is a resultant upward lift. Aerodynamic experts conduct extensive experiments concerning wing sections and even general plane design in artificial winds produced by fans in wind tunnels, to achieve maximum vertical lift and minimum horizontal force or drag.

In all airplanes the essential principle is then to push or pull the plane through the air with a propeller or "air-screw" driven by powerful motors, while the wings provide the required "lift." Control is obtained by variable wing sections. Much work has gone into

[1] Air following along the upper surface travels farther than that along the lower surface, but air in the upper stream goes from front to rear in just the time taken by air in the lower stream—otherwise the lower stream would have to curl upward and contribute air to the upper rear of the section. Thus the velocity (distance/time) in the upper stream must be greater than that in the lower stream.

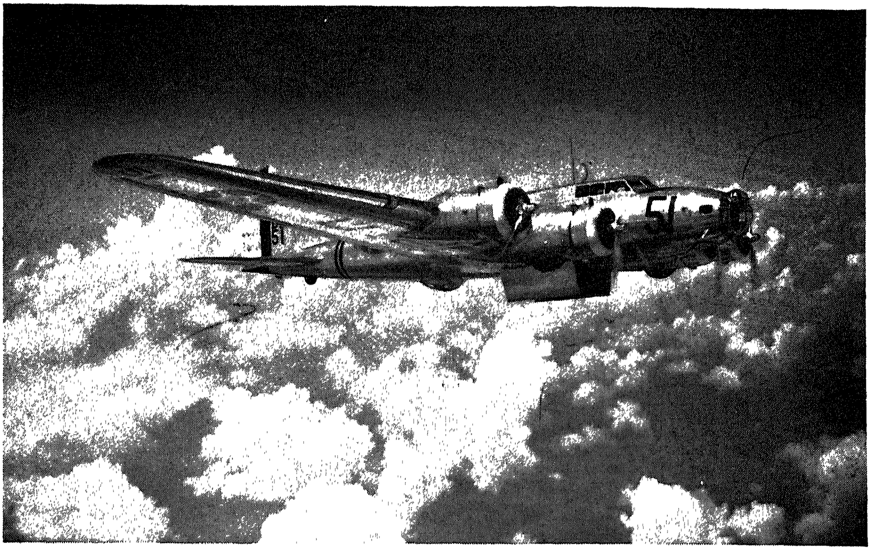


Fig. 327. Boeing "Flying Fortress." Maintains good performance at extreme altitudes. Efficient superchargers compress "thin" air for adequate supply to motors.

the attempt to design all surfaces with minimum drag or air resistance, and with minimum weight for the required strength. Also, tremendous efforts are expended to produce more and more powerful motors with reasonable efficiency and minimum weight per horsepower. Two thousand-horsepower motors with weights of 1.2 lb /hp are in use, and improvements are in progress.

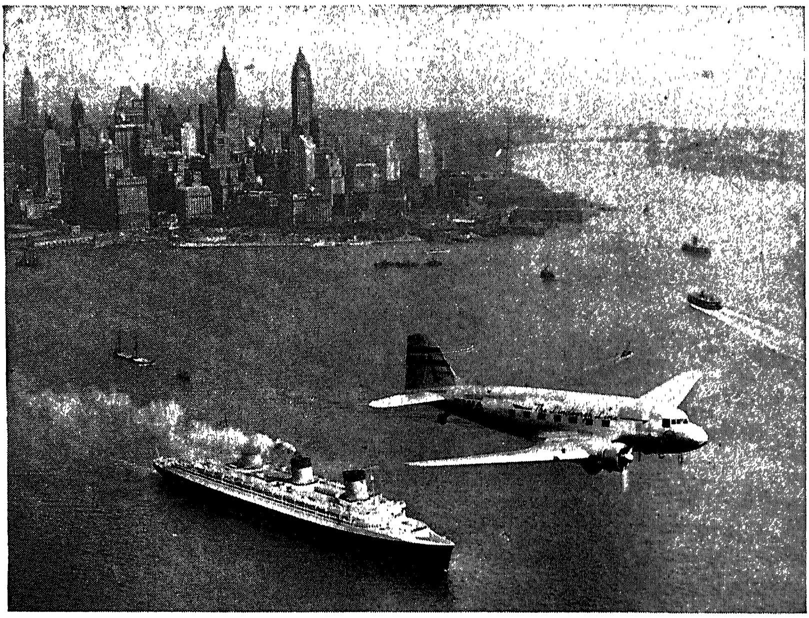
Because air resistance increases almost proportionally to the square of the speed and even more rapidly at speeds above 400 miles per hour, streamlining to reduce drag is exceedingly important in modern planes. "Streamlining" of passenger automobiles is not very important for speeds below 60 miles per hour; so the emphasis on the so-called streamlined car design has been more for aesthetic purposes than for performance.

The airplane, perhaps more than most developments, typifies the great contrast in possible uses and the serious problem of social control. It is on one hand a destructive weapon of unparalleled efficiency, but it also can be a most effective means of making the whole world a single community.

OUR MODERN SLAVES

We asked ourselves how we make use of the power supplied by fuels and water. We have found that the answer is very complex,

and that it is connected in some way with almost every one of our activities. This power carries us where we want to go; it lays road-beds and rolls steel for bridges over which we may pass; it houses, heats, and feeds us; it shears wool and gins cotton, then weaves



(*Transcontinental and Western Air.*)

Fig. 328. Modern transportation.

cloth and forms it into our clothes; it makes armaments to protect us; it brings information to us by telephone, radio, and newspaper; it gives us coffee pots, typewriters, and postage stamps; it prints our books and it provides light to read them by. How we depend upon our modern slaves!

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SUMMARY

One-twentieth of the energy used in the United States is changed to electric or mechanical energy, and the rest goes directly into heat.

From the simple water wheel have evolved the ***Pelton*** or ***impulse wheel*** and the ***reaction wheel.*** These are used chiefly to operate generators.

Modern steam engines usually have tubular-type ***boilers*** delivering steam at high pressures and temperatures. ***Reciprocating steam engines*** are being displaced in many cases by ***steam turbines.*** Steam-electric drives are often used on ships. More than two-thirds of this country's electric energy is generated by steam-electric plants.

Internal combustion engines include the ***spark ignition*** and ***Diesel*** types and the new ***gas turbine.*** Spark ignition engines usually employ the four-stroke cycle and burn gasoline. Diesel engines frequently use a two-stroke cycle in which the fuel is ignited by high compression. The fuel may be an oil less highly refined than gasoline. Diesels find use in trucks and buses, small electric generator plants, and as Diesel-electric drives in lightweight locomotives and ships.

Efficiencies of heat engines are limited by incomplete combustion, friction, heat loss, and also by a factor which is the theoretical efficiency of a perfect heat engine. The latter is $(T_1 - T_0)/T_1$, where T_1°K is the initial gas or steam temperature and T_0°K is the exhaust temperature. Actual efficiencies of steam engines range to about 30 per cent and of internal combustion engines to almost 40 per cent.

The choice of type of industrial power installation depends largely upon economic factors which point more and more toward power by electricity.

Refrigerators are heat pumps in which the refrigerating material is circulated by a pump or, in the Electrolux, by convection. The circulated material absorbs heat from the cooling compartment by evaporation and gives it up to a radiator. If the radiator is outside of a building and the cooling part inside, a simple air-conditioning system results.

In high-speed machinery, engineers are concerned with methods of increasing strength per unit weight and of minimizing vibration.

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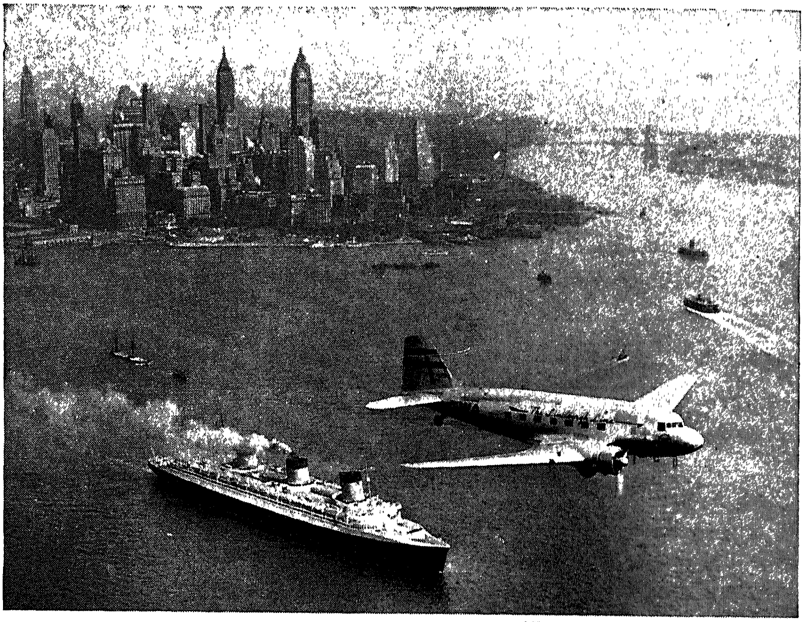

(*Transcontinental and Western Air.*)

Fig. 328. Modern transportation.

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In high-speed machinery, engineers are concerned with methods of increasing strength per unit weight and of minimizing vibration.

Similar problems enter the design of so-called "stationary" structures.

Aeronautical engineers design airplane surfaces to give maximum *lift* and minimum *drag*. Of importance in determining lift is Bernoulli's principle that the pressure in a fluid stream decreases as the velocity of flow increases.

QUESTIONS

1. What fraction of the energy taken from fuels and water in this country is changed to electric energy or used to operate machines?
2. How does a Pelton water wheel differ from a reaction wheel? What is the chief use for wheels of these types?
3. Why is a boiler required for a steam engine? Is there any possible exception to this requirement?
4. What is the cycle of a reciprocating steam engine?
5. How do steam turbines operate? What are their uses?
6. What are internal combustion engines? Heat engines?
7. What are the differences between a Diesel engine and an ordinary gasoline engine?
8. What are the main applications of Diesel engines?
9. With approximately what maximum capacities has it been found practicable to construct the various types of electric generating units?
10. What factors limit the efficiencies of heat engines? What values do the efficiencies attain in practice?
11. What is the over-all efficiency of a steam-electric plant if the boiler efficiency is 80 per cent, the turbine efficiency 30 per cent, and the generator efficiency 95 per cent?
12. How do refrigerators work?
13. How may an air-conditioning system be constructed?
14. Why might it be of advantage to apply the principle of refrigeration for heating purposes?
15. What are some of the problems faced by engineers in high-speed machinery?
16. In what way must engineers take into account energy transfers to "stationary" structures?
17. How is Bernoulli's principle connected with airplane design?

Part III

RADIATION

CHAPTER XV

THE ELECTRON

Before 1900. Near the close of the last century, the various branches of physical science had been brought into an apparently complete ensemble. Consequently, many men believed that few significant discoveries remained to be made in the field of physics. Newton's laws of mechanics, refined and extended by the great mathematical physicists of the eighteenth and nineteenth centuries, seemed adequate for all mechanical problems. Thermal phenomena became an extension of mechanics through the kinetic theory of matter. This theory, which described all matter in terms of tiny indivisible atoms in rapid and continuous motion, was reasonably sufficient. Electric and magnetic phenomena seemed to be well understood as the result of a large group of experiments which included those of Oersted, Ampère, and Faraday. Maxwell had shown that light and electricity are closely related, and he had accounted for their behavior, as then known, by means of his theory of electromagnetic radiation. Newly discovered general principles, such as that of the conservation of energy, emphasized the unity of science and encouraged the idea of a mechanistic universe obeying exact physical laws. It was natural that the set of physical laws then known seemed sufficiently complete. True, there were many questions not entirely answered, but more than a few scientists believed that only refinements of existing theories or extensions of measurements "to the next decimal place" remained to be done.

Such beliefs have probably been expressed in every age since the beginning of time. The Greeks said much the same thing, so also the Romans in their day and the philosophers and ecclesiastics of the Middle Ages. At many times even since Galileo men have been tempted to think that all development in science was done, yet each of these periods has proved to be no more than a pause between advances into the unknown.

Opening a New Era. The period immediately after 1895 brought several major discoveries which completely destroyed the feeling

of self-sufficiency that was creeping into physical science. Outstanding discoveries were that of the *electron* by Sir J. J. Thomson in 1897, of *radioactivity* by Becquerel in 1896, and of *X rays* by Roentgen in 1895. It was during this same period that the practical

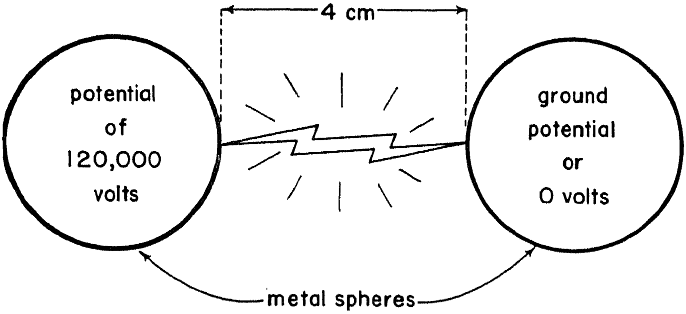


Fig. 329. A potential difference of about 30,000 volts for each centimeter of length of gap is usually necessary to produce a spark between two large smooth metal spheres.

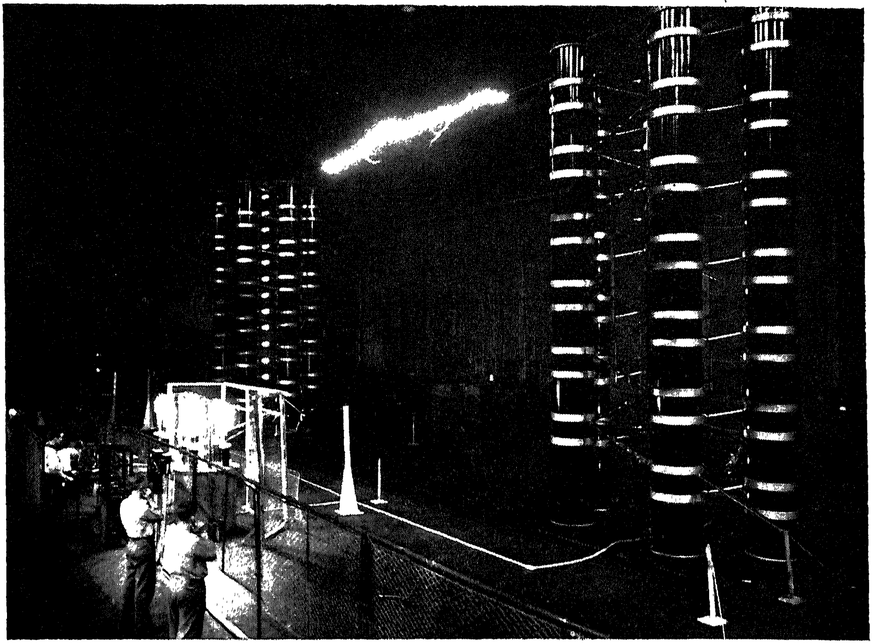
realization of wireless communication by Marconi culminated the work begun by Maxwell and Hertz.

Although these great discoveries initiated the modern age of development in physics, it would be a serious mistake to overemphasize their revolutionary character, for they were actually only steps in the comparatively gradual growth of ideas about the atomic nature of electricity and of matter.

Some of these ideas we have already anticipated, but let us look more carefully at their origin in order to understand better the setting of the story of our present scientific era.

ELECTRIC DISCHARGES IN GASES

Air and other gases are usually very good insulators, but early experimenters with electricity, who worked with crude friction electrostatic machines, learned that when two objects are electrically charged to a sufficiently high difference of potential, the air between them suddenly "breaks down" and becomes conducting so that a spark jumps. We have already seen something of this phenomenon. In dry air under ordinary conditions a spark will jump between large smooth spheres 1 cm apart when about 30,000 volts difference of potential exists between them, but there must be 60,000 volts if the separation is 2 cm, etc. In technical terms, a *potential gradient* of about 30,000 volts/cm is necessary to produce



(*General Electric Company.*)

Fig. 330. Thirty-foot spark produced between points by a potential difference of 7,800,000 volts.

a spark under such conditions. A spark will jump between two sharp points 1 cm apart when the potential difference is much less than 30,000 volts, because then an increased potential gradient of about 30,000 volts/cm is reached very close to each point. Today we say that the air changes from an insulator to a conductor because it becomes "ionized." Also a result of "ionization" of the air is the "leaking" of electricity off wires at high voltages, which, as we learned earlier, sets a practical upper limit to the potential on high-voltage, low-current transmission lines.

"Ionizing" the Air. Air may be "ionized," or made conducting, in many other ways. A charged electroscope is discharged immediately when a hot flame from a match or Bunsen burner is brought near it. This happens whether the electroscope is charged positively or negatively, which suggests that the hot gases of the flame contain both positive and negative charges, the positive charges neutralizing a negatively charged electroscope and the negative charges a positively charged electroscope. A white-hot piece of metal placed near the electroscope leaf works equally well. Also, it was known,

even before their nature was established, that both X rays and the radiation from radium are capable of discharging a charged electroscope.

All these experiments point to the existence in the air itself of

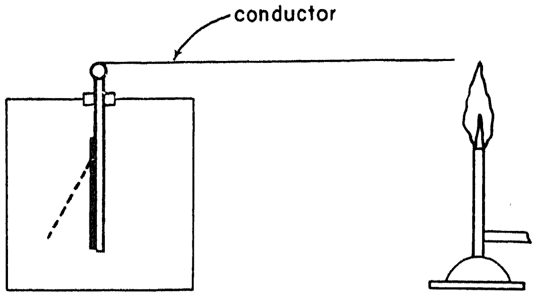


Fig. 331. A flame will discharge a charged electroscope.

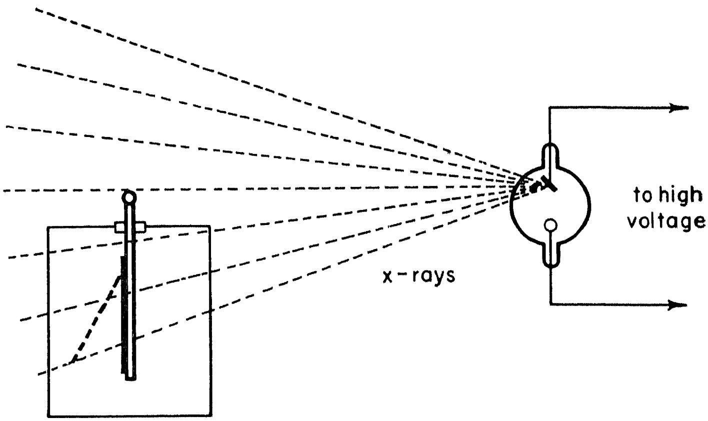


Fig. 332. X rays will discharge a charged electroscope.

electric charges which somehow can be made free. From what we know now, it is only natural to think that if negative charges (electrons) are removed from neutral atoms, the remainder will be positively charged, so that both positive and negative charges, or ions, are produced when electrons are split off the atoms to which they normally belong. A few decades ago this was by no means clear.

Once freed, the electric charges from an ionized gas do not remain free very long. If air from around a hot flame, or from over some radium, is drawn slowly through a tube which has electroscopes mounted along it, the first electroscope discharges quickly, but others discharge successively more and more slowly, and the

last one may show almost no effect. If the ionized air is drawn through rapidly, the electroscopes discharge at a more uniform rate. This seems quite reasonable if we consider that the positive and negative parts of molecules in the ionized air will in time tend

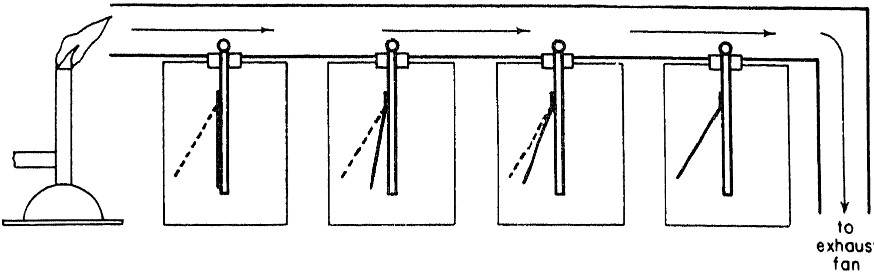


Fig. 333. Electrical charges (ions) liberated in air do not remain free very long.

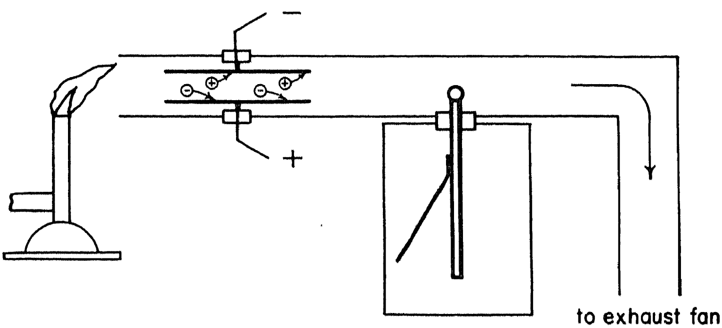


Fig. 334. Electrically charged particles (ions) may be removed from air by passing the air between oppositely charged plates.

to recombine because of their mutual attraction and once again form neutral molecules. Actually, anything that interferes with the free flow of the gases, such as a filter of glass wool, will "remove" the charges from ionized gas by allowing more time for recombination. Even more suggestive is the fact that the electric charges in a gas can be removed quite completely by passing the gas between two electrically charged plates. The positive charges are attracted to the negative plate and the negative charges to the positive plate, that is, they are pulled out of the flowing gas.

It is interesting to note that this is the method used to keep smoke and other fine particles from being blown out over the landscape from the smokestacks in many industrial plants. Such particles frequently are charged electrically, and charge can be sprayed upon the neutral ones. If two electrically charged wires are

placed in the smokestack (or one charged wire inside of a metal stack), the smoke and other charged particles are drawn to one or the other conductor. This system, devised by Dr. Frederick Cottrell, is known as the Cottrell Precipitator. Not only can it prevent

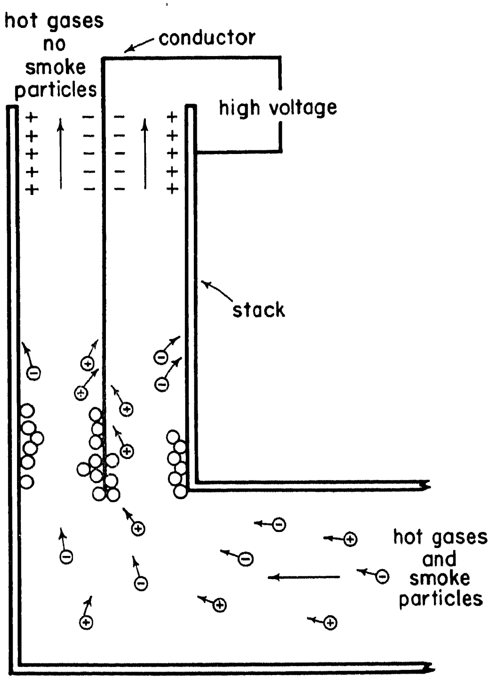


Fig. 335. Principle of the Cottrell Precipitator. Charged smoke particles are attracted to highly charged conductors to which they adhere.

practically all smoke nuisance, but it often recovers valuable chemicals in the precipitated particles. Rather than capitalize on his invention, Dr. Cottrell set up a foundation known as the Research Corporation to administer the sale of this system. The profits are used entirely to support research work on pure science in various universities.

Electric Discharges in Gases at Low Pressure. Much of the knowledge about the nature of electricity and matter has come from studying what happens when electric discharges are set up in gases at low pressures. If air under ordinary conditions can be broken down and made conducting by means of a large potential gradient, simple consequences of the kinetic theory indicate that gases placed in a

partially evacuated tube would become conducting under much lower potential gradients. Michael Faraday did some of the first experiments on electric conduction in rarefied gases. Other pioneers in experiments of this type were Hittorf (1824–1914) and Geissler

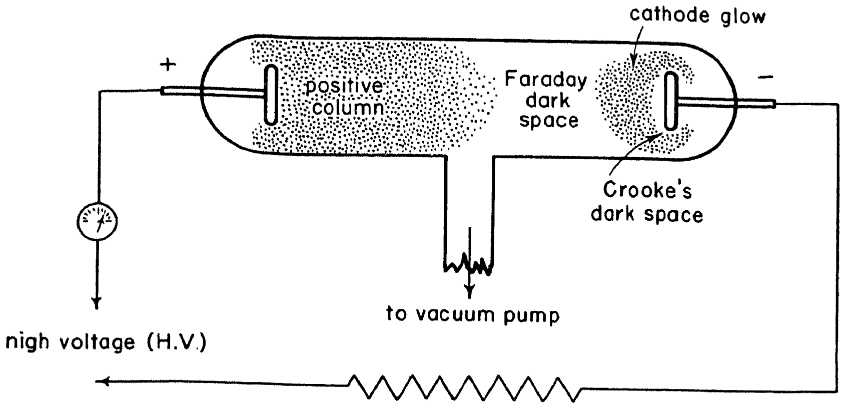


Fig. 336. Intermediate stage of the discharge in a progressively evacuated tube.

(1814–1874) in Germany and Sir William Crookes (1832–1919) in England.

Perhaps we can learn best about the work of these early experimenters if we follow some easy experiments of our own, simplified indeed by the use of modern "vacuum" pumps. The history of our knowledge about atoms and molecules is closely linked to the story of the development of pumps capable of producing a more and more nearly perfect vacuum. To a good "vacuum pump," suppose that we attach a closed glass tube 50 cm long with a metal electrode inserted at each end, and connect the electrodes to a source of constant high voltage, say a DC generator which will give 2,000 volts (Fig. 336). With atmospheric pressure in the tube nothing happens, for the air is a nonconductor when the potential gradient is only 40 volts/cm. The current reading is of course zero.

Now let us start the vacuum pump. No effect is observed until the pressure is reduced to less than 1 cm Hg. Then suddenly the gas "breaks down," and the tube is filled with a brilliant reddish glowing column extending from the positive electrode nearly to the negative electrode. The meter shows that there is a current; and, as a matter of fact, if no resistance were in series with the tube and if the generator could supply enough power, the current would melt the metal electrodes. As the evacuation proceeds, the reddish

placed in the smokestack (or one charged wire inside of a metal stack), the smoke and other charged particles are drawn to one or the other conductor. This system, devised by Dr. Frederick Cottrell, is known as the Cottrell Precipitator. Not only can it prevent

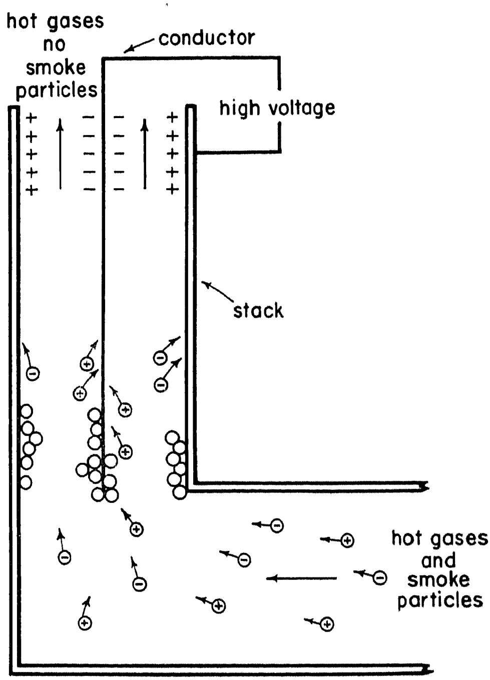


Fig. 335. Principle of the Cottrell Precipitator. Charged smoke particles are attracted to highly charged conductors to which they adhere.

practically all smoke nuisance, but it often recovers valuable chemicals in the precipitated particles. Rather than capitalize on his invention, Dr. Cottrell set up a foundation known as the Research Corporation to administer the sale of this system. The profits are used entirely to support research work on pure science in various universities.

Electric Discharges in Gases at Low Pressure. Much of the knowledge about the nature of electricity and matter has come from studying what happens when electric discharges are set up in gases at low pressures. If air under ordinary conditions can be broken down and made conducting by means of a large potential gradient, simple consequences of the kinetic theory indicate that gases placed in a

partially evacuated tube would become conducting under much lower potential gradients. Michael Faraday did some of the first experiments on electric conduction in rarefied gases. Other pioneers in experiments of this type were Hittorf (1824–1914) and Geissler

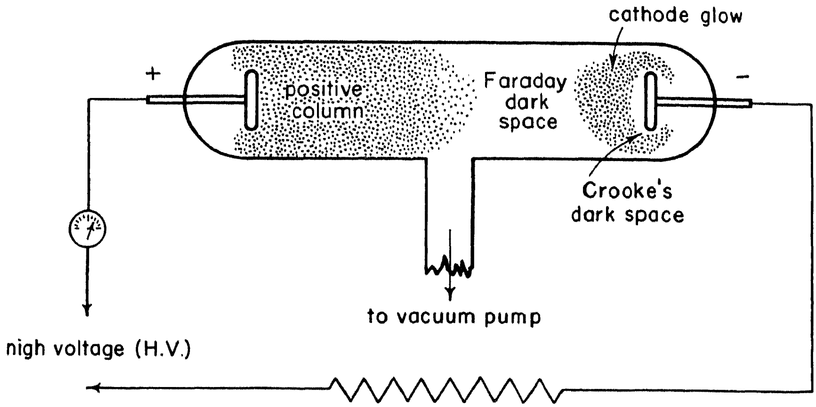


Fig. 336. Intermediate stage of the discharge in a progressively evacuated tube.

(1814–1874) in Germany and Sir William Crookes (1832–1919) in England.

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column, called the ***positive column,*** decreases in length, but at the same time an intense blue glow called the ***cathode glow*** surrounds the negative electrode, the cathode. The space between these glowing regions, which is called the ***Faraday dark space*** in honor of its discoverer, gradually increases in length. While the positive column shortens with further evacuation it often shows "striations"—alternate dark and bright bands. Meanwhile a dark space shows up near the cathode, the ***Crookes dark space.*** As this series of events goes on, the current gradually decreases.

With most mechanical vacuum pumps, the gas still glows faintly at the lowest pressure obtainable. If a pump of the modern "diffusion" type is added to the system, the pressure can be made so low that the glow finally ceases, and the current becomes very small. The glass wall of the tube now has a greenish glow, or fluorescence, as it is called. Finally the current becomes zero—there is so little air left that the space inside the tube is once more an insulator.

Luminous Signs. The luminous gas tube signs seen all around us today are simply discharge tubes with fairly high gas pressure, perhaps 1 cm Hg, so that the positive column nearly fills the tube. Since they are operated on alternating current from step-up transformers, the positive and negative electrodes effectively alternate very rapidly so that the whole tube appears to glow. If ordinary uncolored glass is used, the color is characteristic of the molecules of the gas in the tube. Only the red signs are filled with ***neon*** gas. ***Helium*** produces a pale greenish-yellow color, ***mercury*** vapor gives blue-green, ***argon*** gives a bluish-purple, etc. ***Sodium*** vapor lamps with their characteristic yellow light are being used considerably for highway lighting. The characteristics of the various gases differ so widely that almost any color can be produced.

The efficiency of light sources of this type can be very high as compared to incandescent lamps. A modified mercury-vapor type known as the "fluorescent" lamp is rapidly finding widespread use. We shall see how fluorescent lamps work after we learn more about atomic structure.

Ionization by Impact. The processes occurring in electric discharges in gases are actually quite complex, and for our purposes it is hardly desirable to go into much detail. Sir J. J. Thomson and J. S. Townsend helped much to build up our knowledge of these processes, and later refinements were provided in this country

by K. T. Compton, Irving Langmuir, Bergen Davis, and numerous others.

One important concept does deserve mention, that of ***ionization by impact,*** the chief mechanism by which electric discharges are

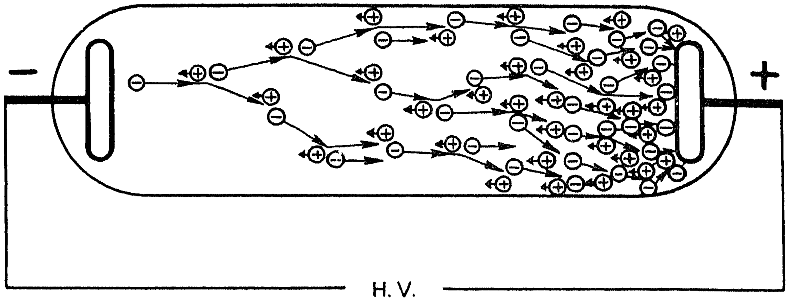


Fig. 337. Mechanism of cumulative ionization by impact. If, on the average, each negative ion liberates more than one pair of charged particles, then one ion can build up a discharge involving many particles.

produced in gases. Neutral gas molecules, of course, do not contribute to conduction. Electric charges must be torn loose from them before there are any carriers of electricity. Sometimes the first electric charges required to start a discharge are ripped from the gas atoms by strong electrical forces resulting from the applied voltage. More often we believe that the residual radioactivity of the surroundings, or the cosmic rays which continually rain upon us, release the first few electric charges. The negative charges are attracted to the positive electrode, and the positive charges to the negative electrode, and these free charges are accelerated by the electrical forces. Ordinarily the negative ions are lighter and thus reach higher speeds than do the positive ions. If, however, the gas pressure is high and the voltage is low, the number of gas atoms per cubic centimeter is so large that the free charges bump into neighboring atoms before attaining a high speed from the electrical forces. We say that the ***mean free path,*** that is, the average distance between collisions, is so small that a real discharge cannot proceed under these circumstances.

But when the pressure is reduced gradually, the number of gas atoms per cubic centimeter becomes so small that the free charges can be accelerated to high speeds before they collide with neutral atoms. If this speed becomes high enough, the charged particles can knock electrons out of the molecules with which they

collide, so that each original free charge might liberate several new charges. These new free charges are in turn accelerated, strike neutral molecules, release more charges, and so a general discharge quickly builds up. A great number of free charges are produced by this cumulative process, and a large electric current, or discharge, results.

This process of cumulative ionization by impact is the mechanism by which most electric discharges are produced. With low potential gradients, low pressures are necessary for a discharge. If the voltage per centimeter is high enough, air, even at atmospheric pressure, may be broken down across distances of many feet, as testified by great man-made sparks from electrostatic machines or high-voltage transformers. The tremendous lightning discharges which rip up the air between charged clouds and earth, or jump from one charged cloud to another, are the same sort of phenomenon except that potential differences of many hundred millions of volts are involved.

Cathode Rays and Electrons. The story of the rays from the cathodes of discharge tubes is worth following for sheer interest as well as for illustration of the scientific method. A long and varied series of experiments with these rays showed incontrovertibly that they are composed of negative particles of electricity, or *electrons* as we call them today, and that the electron is a constituent of all atoms.

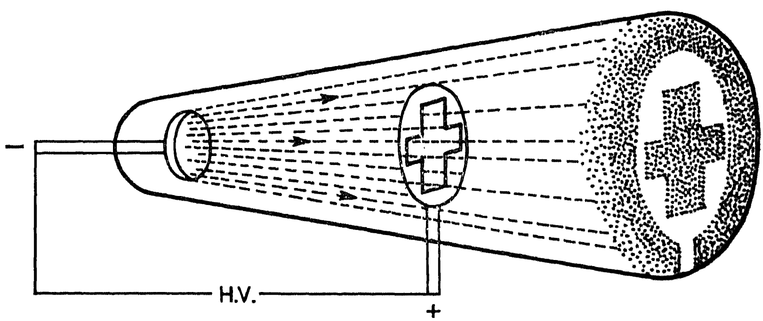


Fig. 338. Cathode rays travel in straight lines. This is indicated by "shadows" cast by objects placed in their path.

The early experimenters finally devised vacuum pumps in which the gas pressure in a discharge could be reduced so low that only a greenish fluorescence of the glass remained to be seen. Under this condition, strange new phenomena were observed. Various

minerals and chemicals such as zinc sulfide, placed inside the tube, glowed brilliantly. Coming from the cathode (negative electrode), was some sort of invisible radiation which seemed to be responsible for this effect. This radiation came to be called the ***cathode ray.***

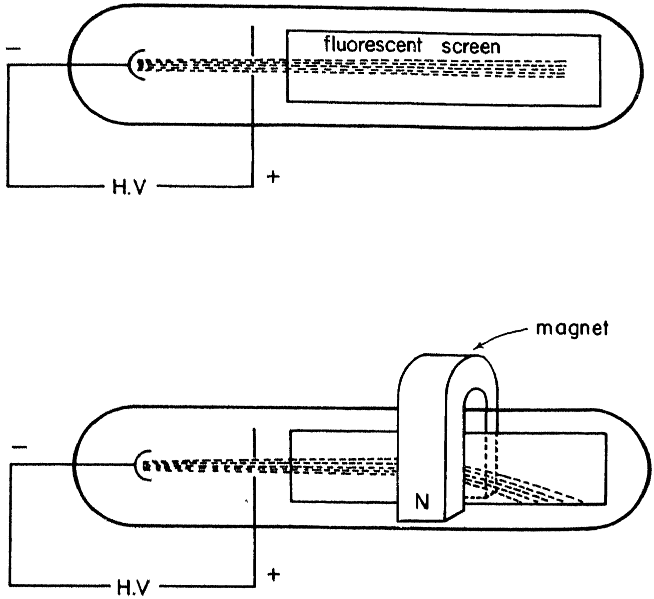


Fig. 339. Cathode rays crossing through a magnetic field are deflected like a current of negatively charged particles.

Opaque objects placed in its path cast sharp shadows on the fluorescing glass walls, showing that these "rays" travel in straight lines. The rays possess energy, because thin foils could be made red hot by their impacts. That they exert mechanical force was indicated by the rotation of paddle wheels and other devices when struck by the rays.

A controversy soon developed as to whether these cathode rays are particles or waves. A significant step toward answering this question was taken when the rays were formed by a slit into a narrow beam and allowed to strike a long fluorescent screen. A horseshoe magnet placed so as to give a horizontal transverse field deflected the particles up or down, depending on the direction of the field (Fig. 339). The rays were shifted in a direction perpendicular to the magnet field and perpendicular to the direction of their motion, just as though acted upon by a force like that on a wire carrying a current of negative electric particles. One obvious

explanation was that the cathode rays actually are negatively charged particles.

Proving the Existence of the Electron. Sir J. J. Thomson (1856–1940) and his coworkers at the Cavendish Laboratory, Cambridge, were

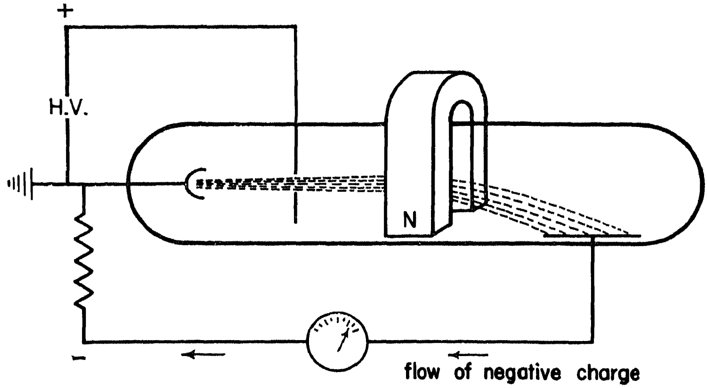


Fig. 340. Cathode rays carry negative electric charges. When cathode rays strike a metal plate there is a flow of negative charge toward the cathode in a conductor leading from the plate to the cathode.

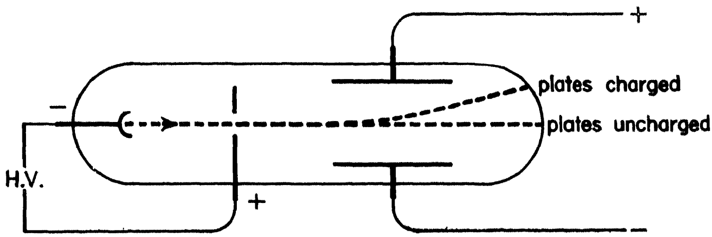


Fig. 341. Cathode rays passing between two oppositely charged plates are deflected toward the positive plate.

among the most active experimenters in settling the question of the nature of cathode rays. The evidence that these are negative particles quickly accumulated. When the rays were deflected by a magnet so as to fall on a metal plate sealed into the wall of the tube (Fig. 340), there was a current of negative charge from the plate, as shown by a sensitive current-measuring instrument. This proved definitely that cathode rays carry negative charge. Still another experiment was even more convincing. The cathode-ray beam was passed between two metal plates before impinging on a fluorescent screen at the end of the tube. When the plates were uncharged, the beam went straight, as before, but when there

was a potential difference between the plates the beam deflected toward whichever plate was positive, just as it should if the cathode rays are negative particles.

Thomson's reasoning carried him far beyond this qualitative

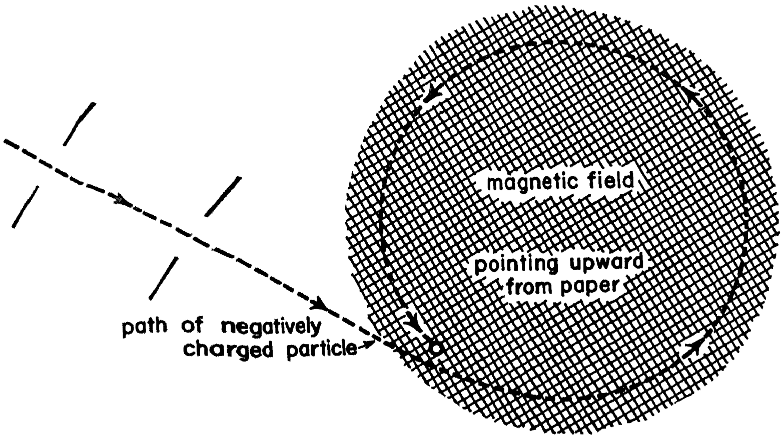


Fig. 342. A negatively charged particle traveling at constant speed traverses a circular path in a uniform magnetic field that is perpendicular to the path.

description. If each of these particles has a definite electric charge and mass, he saw from the work of Ampère and Coulomb that the forces exerted on such particles when moving through a magnetic field, or an electric field between two plates, could readily be calculated. We need not follow the mathematical reasoning in detail, but the essential ideas are quite important because we shall meet them often.

As remarked before, the force exerted upon a cathode-ray beam by a magnetic field is the same as that on a wire carrying the equivalent current. This force, always perpendicular to the direction of motion, bends the beam into a circle with a radius that satisfies the relation

$$\frac{\text{Charge of particle}}{\text{Mass of particle}} = \frac{\text{speed of particle}}{\text{magnetic field} \times \text{radius of path}}$$

If only the speed were known, the ratio of the charge to the mass of the particle could be determined, since the radius of the path and the magnetic field H can be measured.

Thomson devised an ingenious experiment from which to obtain the speed corresponding to the voltage that he used on the

discharge. He sent the particles through both an electric and a magnetic field, such as represented in Fig. 343. The force caused by the electric field alone was arranged to deflect the beam upward. The magnetic field was produced by a coil of wire carrying a current, so that it alone would deflect the beam downward. By properly adjusting the current in the coil and the voltage between the plates, the forces exerted by the two fields could be made equal, so that the effects exactly canceled and the beam remained undeflected. It can be shown that the forces exerted by the two fields were

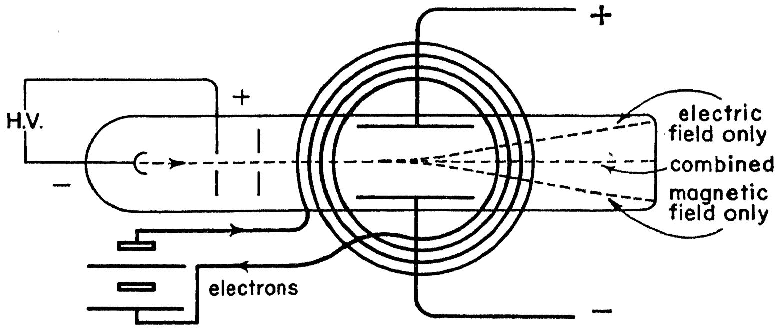


Fig. 343. Thomson measured the speed of cathode-ray particles. The magnetic field of a coil and the electric field between two plates were adjusted so that they would produce equal but opposite deflections of the cathode-ray beam. Then the particle speed becomes just the ratio of the electric-field intensity to the magnetic-field intensity.

Magnetic field force = magnetic field strength × charge on particle × speed of particle

and

Electric field force = electric field strength × charge on particle

Since the two forces were equal, the right-hand sides of the last two equations could be set equal to one another. From this new relation the particle's speed turns out to be just the ratio of the electric field strength to the magnetic field strength. Thomson then calculated the electron speed from measured values of the two field strengths. He found that the speed was about 10^7 meters/sec, suggesting that the particle must be very light. By using this speed value in the result of the experiment on the deflection in a magnetic field alone, the value of (charge/mass) for the particle was obtained.

Thomson showed that, no matter what material forms the electrode from which the cathode-ray particles come and no matter what gas is in the tube, the ratio of charge to mass of one of these particles is ***always the same.*** Careful experiments later showed that this ratio of charge to mass is about 1,800 times the corresponding ratio for the hydrogen ion, obtained in electrolysis experiments. Since the electric charge on both kinds of particle was believed to be the same, Thomson concluded that each cathode-ray particle, or ***electron*** as it was called later, has a ***negative*** charge of about the same value as that on a positive hydrogen ion, and that its mass is about 1/1,800 as great as that of the hydrogen atom.

Measuring the Charge on the Electron. The beautiful series of experiments begun by Thomson gave only the ratio of charge to mass of these newly discovered constituents of ordinary matter, so it was only natural for curious men to seek further information about these particles. For years many of the ablest physicists have attempted to answer multitudes of new questions suggested by these early experiments.

Perrin in France and numerous others devised methods to measure the tiny electric charge on the electron itself. The climax of these attempts was the series of simple and ingenious experiments of Robert Millikan in 1910, at the University of Chicago. He arranged two metal plates so that they could be charged to various potentials by means of batteries. A few tiny oil droplets from an ordinary atomizer were then allowed to drift into the space between the plates, and an observer could follow the motion of one of them from the outside by means of a microscope.

An oil droplet of mass m experiences a downward force mg due to gravity, and, therefore, tends to fall. Millikan was able to obtain the gravitational force mg acting upon any droplet by timing the rate of fall. Then when an X-ray tube was turned on near the apparatus, charged ions were formed between the plates, and one or more of them sometimes attached themselves to an oil droplet. Of course, the mass of a negative ion is so small that it would not be noticed compared to that of an oil droplet. When the upper plate was charged positively by batteries, however, an oil droplet which had a negative ion attached experienced an upward force. By adjusting the battery voltage it was possible to make this

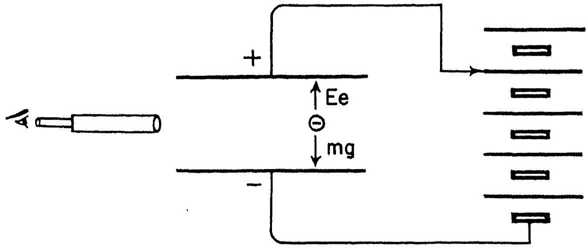


Fig. 344. Millikan measured the magnitudes of minute charges placed on oil droplets and found them to be integral multiples of a common unit. This unit is the charge of the electron. He measured the electrical force Ee necessary to balance the gravitational force mg acting downward on a droplet. Then since he knew the electric field E, he was able to obtain the electric charge e on the droplet.

electrical force on the charged droplet just equal to the downward gravitational force, so that the two balanced and the oil droplet stood still. The electrical force on a particle with charge e, when between two plates separated by a distance d and with a potential difference V, is just Ve/d; so $Ve/d = mg$ for a stationary droplet. It was possible to measure V, d, and mg with great accuracy, so this relation gave a precise value of e, ***the charge of a single electron.*** Actually, an exact balance was so difficult to obtain that similar calculations, but somewhat more involved, were made from measurements of the decrease in rate of fall when a voltage was applied between the plates.

Frequently more than one electronic charge was on the chosen droplet, sometimes even five, ten, or more, but the measurements showed that the ***total charge on a droplet was always an exact multiple of a single elementary charge.*** Millikan's work, recently revised slightly, gives the charge on a single electron to be

$$e = -16.0 \times 10^{-20} \text{ coulomb}$$

The measurement of this exceedingly small quantity of electricity was a triumph of experimental technique.

We might mention now that in ***one ampere*** of current there are

$$\frac{1}{16.0 \times 10^{-20}} \quad \text{or} \quad 6.25 \times 10^{18} \textit{ electrons}$$

which move through any section of the conductor per second (because one coulomb of charge per second is an ampere).

We can go even a step further and find the mass of an electron. Measurements of the ratio of charge to mass for an electron, such as we considered previously, have given $e/m = -1.759 \times 10^{8}$ coulombs per gram. From this and the value of e, we have

$$\text{Mass of an electron} = \frac{-16.0 \times 10^{-20}}{-1.76 \times 10^{8}} = 9.1 \times 10^{-28} \text{ gram}$$

This almost infinitesimal mass of an electron is, as Thomson supposed, nearly 1,850 times smaller than the mass of a hydrogen atom!

You might also ask, "How big are electrons?" Measurements answering this question are much more indirect than those just described and depend upon the meaning of size. The apparent "boundary" of an electron is usually set by electrical forces between the electron and other charged particles. Electrical force fields, however, extend indefinitely; so the meaning of "size" of the electron is necessarily hazy. Our best idea of electron size comes from measurements of collisions between electrons, based on techniques of which we shall learn more later. The results indicate that the effective diameter of an electron is about 10^{-13} cm. For comparison, the diameter of a hydrogen atom is approximately 10^{-8} cm, that is, about 100,000 times as great. The electron, this tiny unit of electric charge and mass, is an essential building stone of all atoms. Because of its prevalence, it is bound to play an important role in nearly all phenomena of nature.

Cathode-ray Tube. As one of the outcomes of researches on cathode rays, there has evolved an instrument which is a most useful laboratory tool, as well as one of the essential elements in television reception. The ***cathode-ray tube*** is but one example of the electronic devices which today are being adapted to a variety of purposes not dreamed of a few decades ago. The modern cathode-ray tube utilizes a hot filament for the source of electrons. The electrons are frequently accelerated by being attracted toward a positively charged screen through which they pass. Equally important, however, they are ***focused*** into a narrow beam by the action of the electric fields near several electrically charged rings. The cathode rays in passing through these fields behave much like ordinary light "rays" going through curved glass lenses. (The field of re-

search which involves such "electron lenses" is actually called "electron optics.") From the focusing fields the beam passes between one pair of horizontal metal plates and then between another pair of vertical plates.

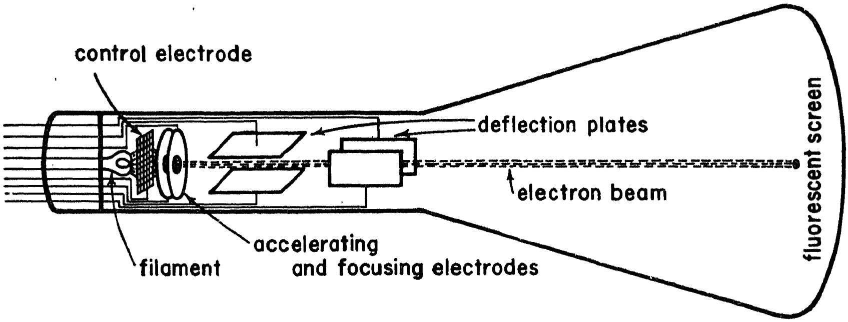


Fig. 345. Diagram of a simple cathode-ray tube. The vertical position of the spot that the electron beam produces on the fluorescent screen is controlled by the left-hand set of deflection plates, and the horizontal position by the right-hand set.

When the plates are uncharged, the electron beam goes straight through and causes a tiny spot of intense light where it strikes a fluorescent screen on the end of the tube. When a potential difference is applied to the first set of plates (the horizontal plates) the electron beam moves up or down on the screen, being deflected toward the plate which is made positive. The beam may be deflected horizontally at will by applying a potential difference to the second set of plates. The amount of deflection is proportional to the voltage between the parallel plates. The electron beam thus strikes the screen at a position which changes with the voltage applied to the deflecting plates. Since the electrons have such a tiny mass, the beam is practically a perfectly weightless pointer which responds almost instantly to changes of voltage on the plates.

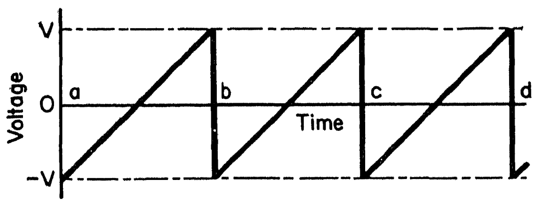


Fig. 346. "Saw-tooth form" of the voltage variations supplied by the linear sweep circuit of a cathode-ray tube.

Usually, a potential difference which varies with time as in Fig. 346 is applied to the vertical plates by means of a "linear

sweep circuit." Under the influence of this voltage the electron beam starts at one side of the screen and moves horizontally at a steady rate during the time interval ab. At the instant b, the voltage suddenly drops from v to $-v$; so the electron beam dashes back to

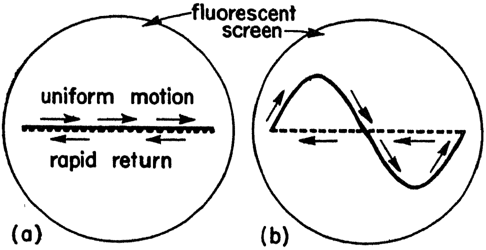
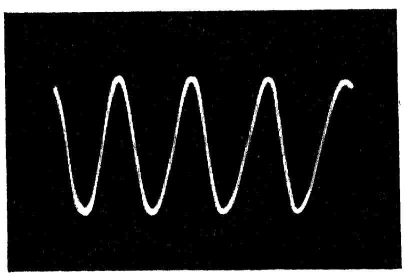


Fig. 347. Patterns of recurring voltage variation can be traced on the screen of a cathode-ray tube. (a) Horizontal line retraced each $\frac{1}{60}$ sec by the linear sweep circuit. (b) Vertical deflections produced by 60-cycle AC are stretched out by the horizontal motion of (a) to retrace time after time the "form" of one cycle of the AC.

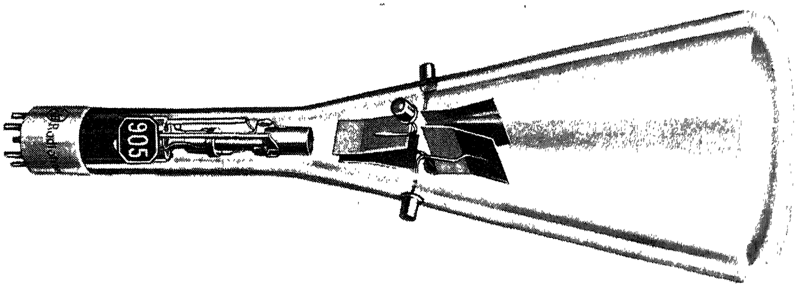
its initial position so quickly that it scarcely leaves a visible trace on the screen. During the time bc, the beam moves steadily across the screen once more and repeats what went on before. With such a recurrent uniform motion of the beam in the horizontal direction, the cathode-ray tube may be used to observe regularly changing voltages applied between the vertical deflecting plates. For example, suppose that the 60-cycle power lines (requiring $\frac{1}{60}$ sec for one complete voltage alternation) are connected to the plates which give vertical deflection, and the sweep circuit is adjusted so that the beam makes a full horizontal traversal in exactly $\frac{1}{60}$ sec. Then during one horizontal "sweep" the beam can move upward from zero to a peak position, back to zero and on to a negative minimum, then upward to zero again, as it follows the voltage variations between the power lines. Meanwhile the motion is stretched out horizontally so that it represents the 60-cycle wave form (Fig. 347). If the horizontal sweep frequency is timed to match the other frequency exactly, the beam almost instantly dashes back to the starting point (along the dotted line in Fig.



(Radio Corporation of America.)

Fig. 348. Pattern of several cycles of AC photographed on the screen of a cathode-ray tube.

347) at just the right time to start retracing the entire cycle. Thus, successive traces fall on top of one another so rapidly that they produce a stationary pattern. Such a fast "pointer" can follow variations with almost no delay and requires so little power



(*Radio Corporation of America.*)

Fig. 349. Cathode-ray oscillograph tube.

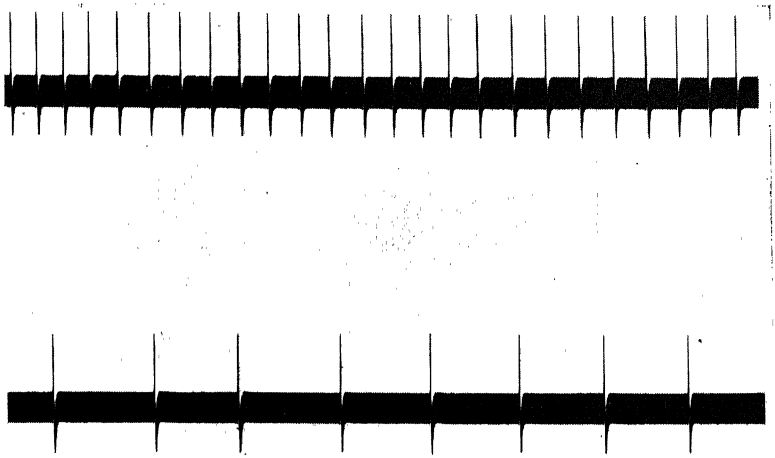
that it is an unsurpassed tool to show clearly high-speed electrical phenomena which otherwise could not be followed. Often the term ***cathode-ray oscilloscope*** is applied to such a device.

Television. In television the electron beam of a cathode-ray tube makes an ideal high-speed "paint brush" which traces the received picture on the fluorescent screen. The fast-moving electron beam is made to travel back and forth, while shifting vertically, so as to cover a rectangular section of the screen. At the same time the intensity of the electron beam is caused to vary (by an additional electrode) in such a way that it follows faithfully the original variations in light intensity from the picture or scene being televised. We shall meet television processes in greater detail in Chap. XVII.

The Cathode-ray Tube in Biology. The cathode-ray oscilloscope has become one of the most useful tools in biological research. There seems to be a general rule that any physiological action is accompanied by an electric impulse, and the cathode-ray indicator is an ideal instrument with which to study these electrical changes. The so-called "brain waves" associated with mental processes belong to this type of manifestation.

Another striking example of this phenomenon is that voltage pulses picked up from the ear mechanism can be made to reproduce the sound which gives rise to them. In other words, a cat's ear,

say, can be used as a microphone. These electrical variations are not the same disturbances as are sent to the brain from the inner ear, for the latter have no resemblance in form to the sound waves producing them.



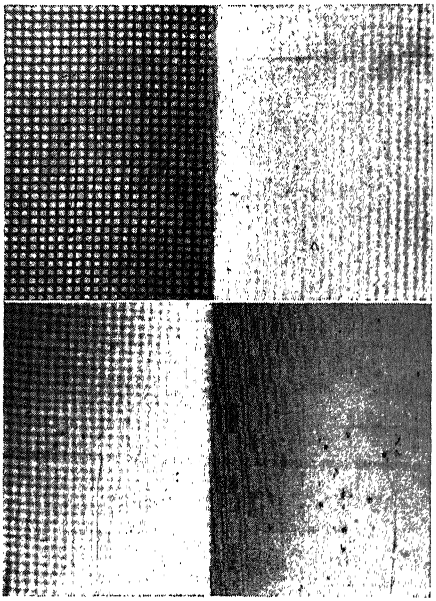
(*H. K. Hartline.*)

Fig. 350. Oscillograph records of the amplified potential changes in a single optic-nerve fiber (eye of Limulus) due to steady illumination of the eye. Intensity of illumination is ten times greater for the upper record than for the lower one. Note that higher intensity of illumination simply increases the number of nerve impulses per second and does not change the shape of the impulses. Full length of record corresponds to 1 sec.

The cathode-ray tube and vacuum tube amplifier (Chap. XVII) have opened for study the rich field of physiological phenomena, such as the nerve action-potentials which carry the messages from sensory organs to the brain over an intricate communication system and so reveal to us phenomena in the outside world. When a nerve fiber transmits a disturbance the oscillograph record looks like a series of sharp pulses which are similar in character for all types of nerve. The only difference is that the number of pulses per second traveling along a fiber to the brain increases, for example, with the intensity of light or sound received by the eye or ear.

The Electron Microscope. Phenomena never before visible have been revealed through new electron lens techniques. Ordinary optical microscopes cannot be used to view objects less than about 4/100,000 cm in diameter. This lower limit is the shortest wave length of visible light, and, regardless of the magnification

employed, ordinary light is so "coarse grained" that all objects of about the same dimensions as the wave length of the light appear indistinct. The tiny electron makes an ideal substitute for relatively "coarse" light, and experience with simple electron lenses (page



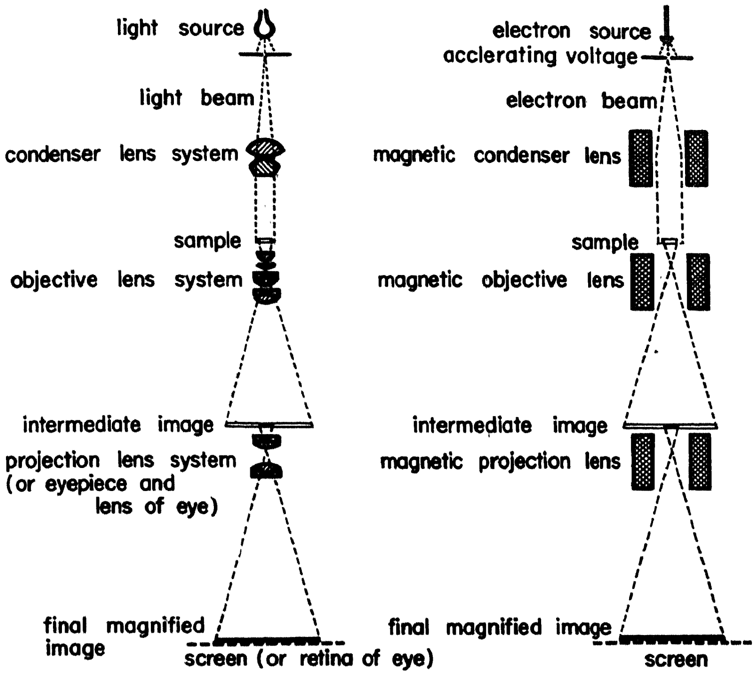
(*Photo Technique.*)

Fig. 351. Effect of wave length of light and diameter of objective-lens opening on image detail. Photographs at left with blue light show more detail than those at right with red light. Photographs at top with large lens opening show more detail than lower photographs with smaller opening.

455) has led to the development of electron microscopes which far surpass their optical relatives.

The essential lens systems for electron and optical microscopes are quite similar. Instead of being glass, electron lenses are either the electric fields near holes in electrically charged plates or the magnetic fields produced by currents in coils of wire. These "lenses" bend and focus the electron "rays" in the same way that glass lenses focus "rays" of light. Figure 352 shows the arrangement of an electron microscope. The whole apparatus must be evacuated. Electrons speeded up by high voltages and concentrated by a "condenser lens" are passed through a thin specimen. An enlarged electron shadowgram image, resulting from the differ-

ing electron opacity of various portions of the sample, is then produced by a magnetic objective lens, and another enlargement is provided by a second magnetic lens. Finally the electron image, magnified 25,000 to 100,000 times, is focused on a fluorescent

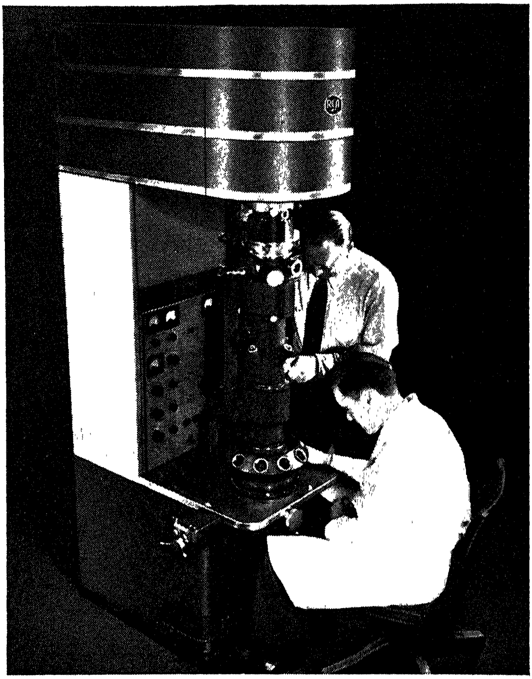


(*After drawings from Radio Corporation of America.*)

Fig. 352. Diagram of electron microscope (right) and, for purposes of comparison, diagram of optical microscope.

screen as in a cathode-ray tube, and there it may be viewed directly or photographed. Already, objects 100 times smaller than can be studied with ordinary microscopes have been photographed. The pictures are so clear that they can even be enlarged further by optical means.

Careful engineering by Zworykin, Marton, and their collaborators has transformed this new microscope into a simple device which can be used with comparative ease. What new discoveries will the electron microscope uncover in biology and medicine, as well as physics and chemistry? New bacteria, new viruses, and even many giant molecules should be within its range. No one can



(*Radio Corporation of America.*)

Fig. 353. Electron microscope. Dr. V. K. Zworykin (standing) and Dr. J. Hillier.

(a) (b)

(*Radio Corporation of America.*)

Fig. 354. Photographs made with electron microscope. (a) Face powder, magnified 35,000 times by the electron microscope (reduced to 11,000 times in printing). (b) Bacillus Streptococcus haemolyticus, magnified 25,000 times by the electron microscope (reduced to 8,000 in printing).

tell yet exactly what will be found, but we can be sure that extending our vision to one-hundredth of its former lower limit will open many new vistas.

LIGHT QUANTA AND ELECTRONS

The Photoelectric Effect. About 1880, the German physicist, Heinrich Hertz, who was experimenting with spark gaps and dis-

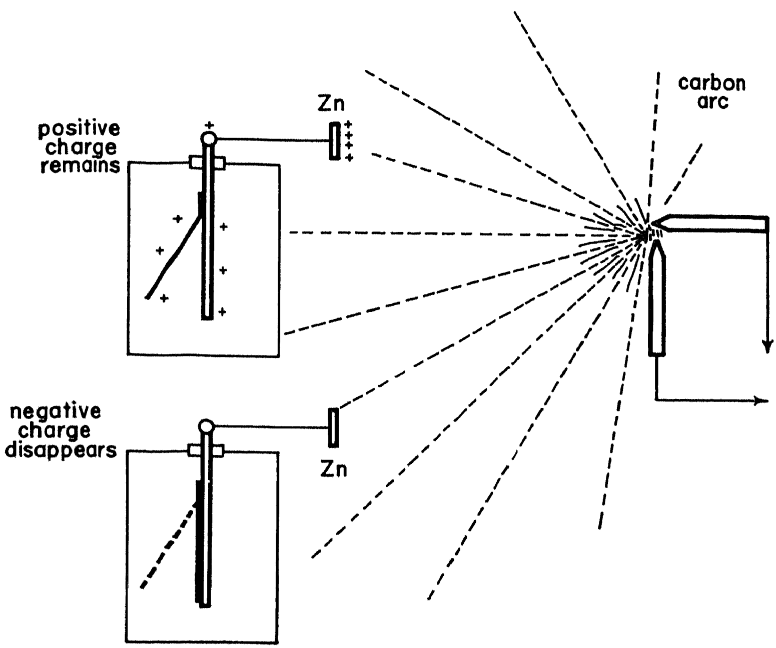


Fig. 355. Hallwachs discovered that the radiation from a carbon arc removes negative charge from a zinc plate but does not affect a positive charge.

charges in electric circuits, made the somewhat puzzling observation that a spark gap, when illuminated by strong light from an electric arc, would "break down" with much lower voltage than normal. This went unexplained until some years later when Hallwachs, a fellow countryman of Hertz, performed some enlightening experiments. Let us re-create these studies. If a freshly scraped zinc plate is attached to an electroscope and the whole is charged positively, nothing whatever happens when the zinc plate is illuminated by strong light from an arc discharge between two

carbon electrodes. When the electroscope is charged negatively, however, the electroscope leaf quickly drops. If a sheet of glass is interposed between the arc and the zinc plate the discharging effect ceases.

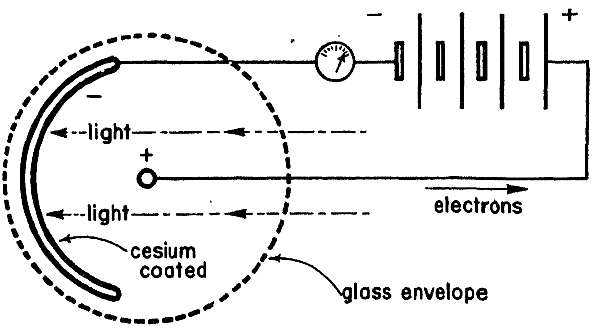
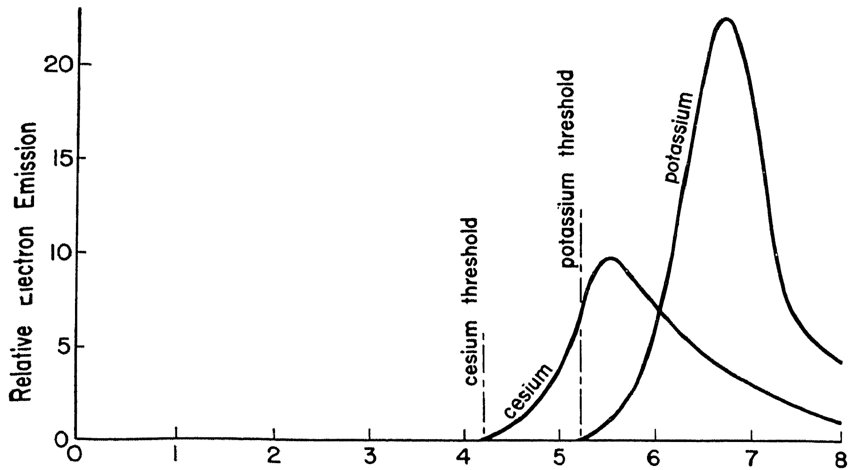


Fig. 356. Photocell. Light striking the cesium-coated surface produces current in the external circuit.

Something from the arc, which cannot pass through ordinary glass, is somehow able to "pull off" negative charges from the zinc plate and so discharge the electroscope. The commonly known fact that "ultraviolet" light, the invisible light just beyond the violet part of the spectrum, cannot go through ordinary glass gives a clue that the ultraviolet light is somehow responsible for this action. The clarification of the details of these ***photoelectric*** phenomena required patient investigation by many experimenters. Some believed that the air took an essential part in the process, but when the metal surfaces were enclosed by quartz vacuum envelopes, which pass ultraviolet light, the photoelectric effect worked even better than before. The "alkali metals" lithium, sodium, potassium, rubidium, and cesium (see the periodic chart, page 192) were found to be especially effective photoelectric emitters. Cesium serves particularly well, even with visible light.

Photoelectrons. When a metal of the group mentioned is placed in a vacuum, negative charges are "pulled off" by the action of light of sufficiently short wave length. If a second electrode is placed in the vacuum and charged positively by means of a battery, the negative particles are attracted to the positive electrode and produce easily measurable currents when the outside circuit is completed. Such a device is called a ***photoelectric cell,*** or just ***photocell.***

As might be expected, there is no current when the second electrode is charged negatively, because negative charges then are repelled. Experiments by Thomson and others showed that these negatively charged particles, called ***photoelectrons,*** are deflected



(*Data from Miss E. Seiler.*)

Fig. 357. For each photoelectric substance there is a threshold frequency value. In other words, light with a frequency below that value cannot produce photoelectric emission. Photoelectric emission depends not only upon the photosensitive substance but also upon the treatment of the exposed surface, etc.

in magnetic fields and behave exactly like the cathode-ray electrons, even to having the same charge and mass.

Dependence on Light Intensity. As long as the light frees photoelectrons at all, the current, or the number of electrons ejected per second, is directly proportional to the light intensity. (We may recall that intensity is the rate at which energy falls squarely onto a surface of unit area.)

Dependence on the Wave Length or Frequency of Light. Of visible light, red light has the longest wave length, or lowest frequency, and violet light the shortest wave length, or highest frequency. If various frequencies of light are allowed to illuminate a pure metal in a photoelectric cell, a very peculiar effect is observed: ***No photoelectrons whatever can be ejected, no matter how intense the light, unless the frequency is sufficiently high.*** There is a definite ***threshold*** or ***lower frequency limit*** for each metal, below which the process cannot take place.

For a long period this seemed almost impossible to understand, because light was considered to be a conventional sort of wave motion which transfers an amount of energy that is directly proportional to the time of action. At the time of its discovery, practically no other known phenomenon had such a critical frequency limit as that exhibited by the photoelectric effect.

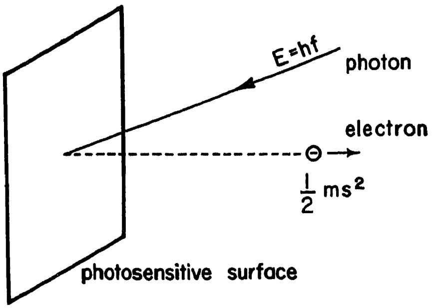


Fig. 358. Photoelectric process. A photon striking a photosensitive surface pulls out an electron. Part of the energy of the photon is required to free the electron from the surface and the remainder appears as kinetic energy of the electron.

The Quantum. A reasonable explanation of this sharp frequency cutoff was given by Einstein, following an idea which Max Planck had proposed some years earlier. In trying to find an explanation for the distribution of the energy radiated by a hot body, Planck had introduced the idea that light is not given off as a continuous wave motion, but instead in little packets or bundles of wave energy which he called *quanta*. The amount of energy in each quantum of light was taken to be proportional to the frequency, so that the energy of a quantum is

$$E = h \times \text{frequency} = hf$$

where h (now called Planck's constant) is a universally applicable constant.

Planck's concept that light is composed of individual quanta, sometimes called photons, each with an energy proportional to the frequency of the light, worked remarkably well in the explanation of the sort of radiation emitted by hot objects like lamp filaments or the sun. At first, however, many thought it a mere mathematical trick which happened to agree with observations.

Einstein said that the quantum idea also would explain the photoelectric effect very simply if regarded like this: Electrons in a metal are to a certain extent bound to the atoms, and some definite minimum energy, say E_0, will always be necessary to pull an electron away from the atoms holding it. The amount of energy required will depend upon the type of atom. Then the law of con-

servation of energy applied to the ejection of a photoelectron by a photon gives

Energy of ejected electron = (energy of light quantum) − (energy necessary to pull electron away from the atoms)

or

$$\tfrac{1}{2}ms^2 = hf - E_0$$

where $\tfrac{1}{2}ms^2$ is the kinetic energy of the ejected photoelectron.

This tells us the whole story. The photoelectric process is the absorption of a single light quantum by a single electron. The incident light quantum or photon can liberate the electron from an atom only when it has an energy, $E = hf$, which is larger than the critical amount $E_0 = hf_0$, in other words, when it has a frequency greater than $f_0 = E_0/h$. If the frequency is greater than this threshold value, the electron is given additional kinetic energy. The experimental investigations of photoelectricity are in complete accord with this simple but revolutionary concept that light is a stream of individual wave energy units.

Powerful support for the quantum view of photoelectricity comes from the development of instruments so sensitive that they can detect a single photon and the single photoelectron which it ejects. Since its first successes, the quantum theory has provided the interpretation of so many varied phenomena that now it is considered to be firmly established.

Photoelectricity in Use. The photocell is being applied to many diverse uses, and much research has been done for the purpose of extending its sensitivity and usefulness. It is essentially a device for converting light energy into electric energy. Many of the photocells in use consist of a collecting electrode and a metal plate carrying the light-sensitive material, both sealed in a glass tube highly evacuated or filled with inert gas. Mass production methods make it possible to manufacture these cells quite inexpensively.

It is possible to make photocells especially sensitive to almost any desired color region. By using complex surfaces, such as a combination of cesium-oxygen and silver, cells have been made sensitive throughout the visible region, in the red as well as in the violet.

A different kind of cell now in common use, of which the Weston photronic cell is typical, does not even use a glass vacuum envelope.

Here the light-sensitive surfaces consist of thin semitransparent deposited layers of several elements, such as iron and selenium or copper and cuprous oxide. Such layer cells not only become conducting under the influence of light, but also generate enough voltage themselves to operate small devices without the aid of batteries.

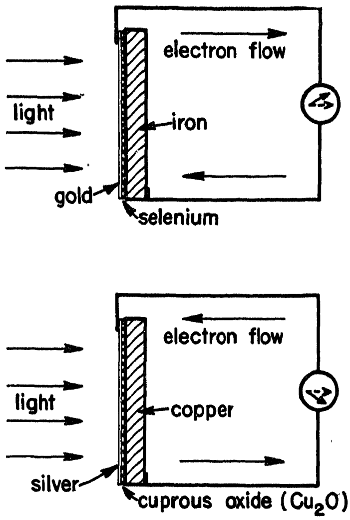


Fig. 359. Two forms of photovoltaic cell. This type of cell, when acted upon by light, generates enough voltage to operate small indicators without need of a battery in the external circuit.

This type of cell is used especially in a wide variety of meters for measuring light intensities, particularly for photography. For such use the photoelectric cell is usually connected to a sensitive current-measuring instrument which is calibrated to indicate directly the light intensity, or else the proper camera shutter time for a given stop opening (*f* number) and film "speed." Instruments of this type are being used more and more to test accurately the intensity and distribution of light in homes, offices, and factories in order to determine whether the illumination meets satisfactory standards.

Human Eye and Photocell. The human being is visually a poor judge of light intensity, just as he is of sound intensity (page 259). Although the eye itself is exceedingly sensitive, compensation devices automatically increase or decrease the response, depending on the intensity of the light stimulus. The *iris diaphragm* of the eye closes to progressively smaller openings for light of increasing intensity and likewise opens more and more as the light intensity weakens. Moreover, the action of the iris can be affected by factors other than light, for example, the reaction to fear or intoxication, and the dilating influence of belladonna. Naturally these effects, as well as many subjective, psychological shortcomings, make us inherently unreliable in gaging light intensity. The photo-electric cell, on the other hand, can be calibrated to give the correct absolute intensity of light, free from all personal or psychological bias.

The eye itself is, in a sense, a photoelectric cell, and a marvelous one. The lens, like that of a camera, focuses the image of the out-

side world on the ***retina,*** which is a photoelectrically sensitive surface. Selig Hecht has found by direct measurement that 50 to 150 quanta of light must strike the outer surface of the eye, the ***cornea,*** in order to give a perceptible flash of light. For average

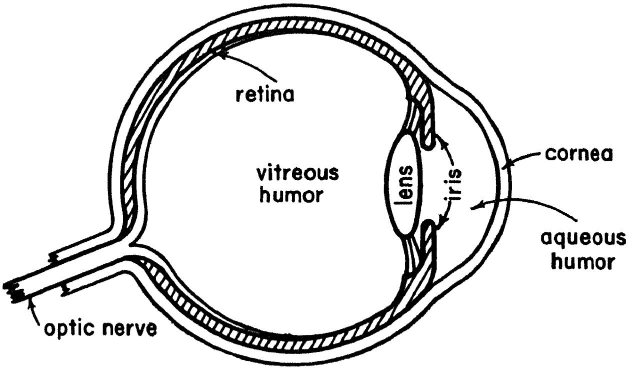


Fig. 360. The human eye.

visible light, 100 quanta possess the almost inconceivably small energy of 3×10^{-17} joule. Another way of saying this is that the tiny amount of energy given up by one drop of water in falling one centimeter is more than enough to give a light flash to every person who ever lived! After reflection at the surfaces of the eye and absorption in the nonsensitive parts, only about ten quanta are actually absorbed by the retina in a just perceptible light flash.

The pioneer work of Boll, Kühne, and von Helmholtz on the nature of vision has been extended by many able physiologists and biophysicists so that we are beginning to have a fairly complete idea of vision processes. The reactions which occur in the retina are ***photochemical,*** that is, they are chemical reactions, the nature and speed of which are changed by the absorption of quanta of light energy. Photographic images have actually been fixed on freshly removed retinas of frogs and rabbits. In the active cells of the retina, called "rods" and "cones," there have been found several light-sensitive substances usually referred to, from their color, as "visual purple." Light bleaches these photosensitive substances, breaking them down, and in so doing produces an electrical disturbance which is carried by the optic nerve to the brain where the vision process is completed. The visual purple is regenerated automatically—this is noticed in the increased ability to distinguish faint objects after eyes have been in the dark for a while, or

"dark-adapted." Vitamin A plays an important part in this sensitizing process. The various photochemical reactions in the eye have different color sensitivities, and color blindness is simply the defectiveness of one or more components in these reactions.

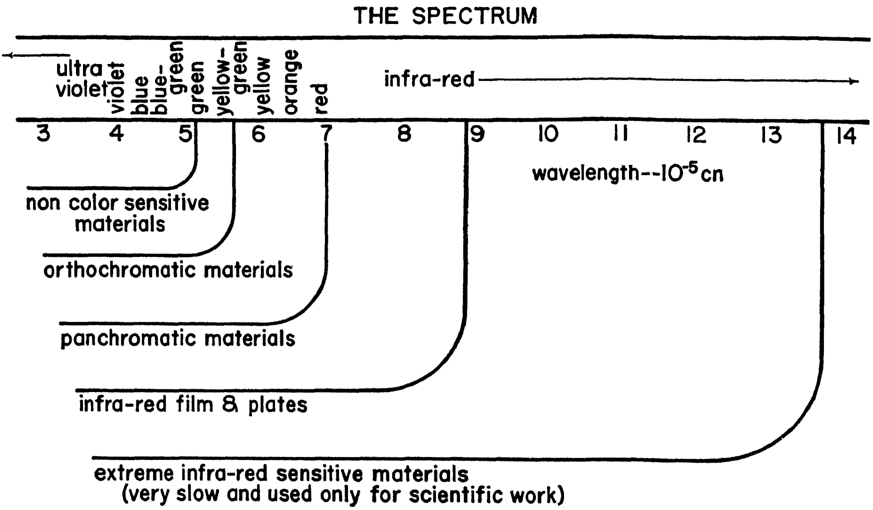
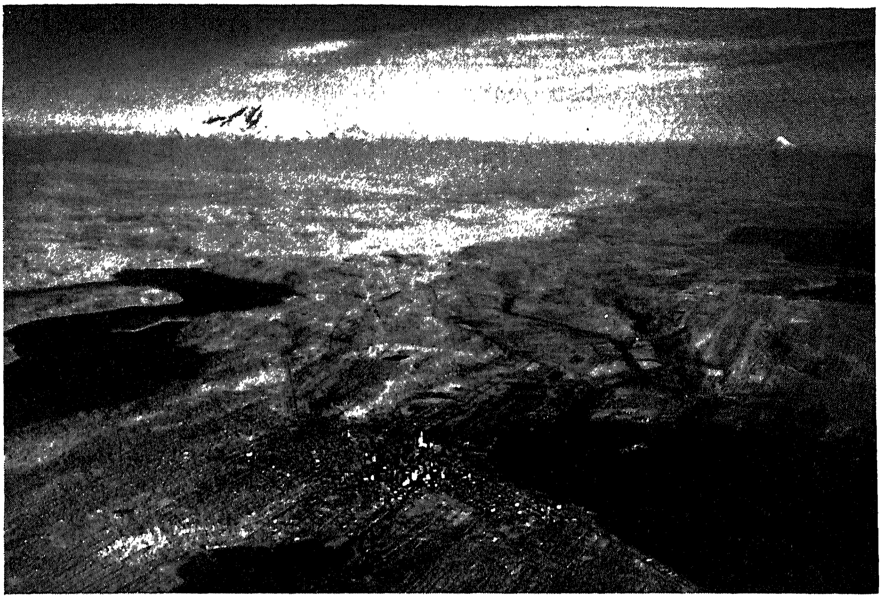


Fig. 361. Sensitivity ranges of various types of film.

Photography. The image on a photographic plate is also the result of the energy given by light quanta to molecules in the emulsion, particularly in the cases of certain molecules like silver bromide (AgBr) and silver iodide (AgI). The explanation often given is that a photoelectron released from the Br^- ion by a photon neutralizes the charge of the Ag^+ ion in the molecule and so produces a free silver atom. By suitable "development," metallic silver is produced in different sections of the plate in amounts which vary according to the gradations in light intensity, so it may be made to show up as an image. (See page 544.)

The first photographic plates made by Daguerre about 1835 were sensitive only to the comparatively high-energy violet quanta. Use of photosensitive dyes has made possible modern "panchromatic" emulsions, the sensitivity of which includes relatively low energy red photons. Special plates have been made sensitive even to invisible infrared photons of still lower energy.

Photosynthesis. Life on this world depends upon the chemical reactions made possible by the energy which photons from the sun give to electrons. To manufacture organic material from carbon



(*Bradford Washburn.*)

Fig. 362. Infrared rays penetrate fog and haze. Here Mount Rainier, with Seattle in the foreground, was photographed at 10,000-ft altitude and at a distance of about 75 miles on Eastman Infrared Aero Film.

dioxide, water, and simple salts, all green plants require the action of light quanta on ***chlorophyll,*** the green coloring matter of plants.

Photoelectrons at Work. Glass wall photocells of the vacuum or gas-filled type give rather small currents with ordinary light intensities, and so they are frequently used with vacuum tubes which "amplify" their currents (Chap. XVII). All sorts of devices can be operated by this combination. A typical arrangement which would make a fine burglar alarm, but can also be used to do a great variety of things, is shown in Fig. 363. Light from a small lamp is focused by a lens on the sensitive surface of a photocell where it liberates photoelectrons. (Invisible ultraviolet or infrared light can be used.) The amplified current from the photocell is then sent through the coil of a ***relay*** where the magnetic field that it produces pulls down a hinged iron strip to which contacts are attached. As arranged in the diagram, the contacts to an electric bell circuit are normally separated so that nothing happens as long as light falls on the cell and there is current in the relay. When someone interrupts the light, by walking between the light

and the photocell, the current stops, the relay arm is pulled back, the bell circuit is closed, and the alarm sounds.

Tireless electrons can be made to do almost anything. A circuit can be arranged so that any apparatus can be switched off or on

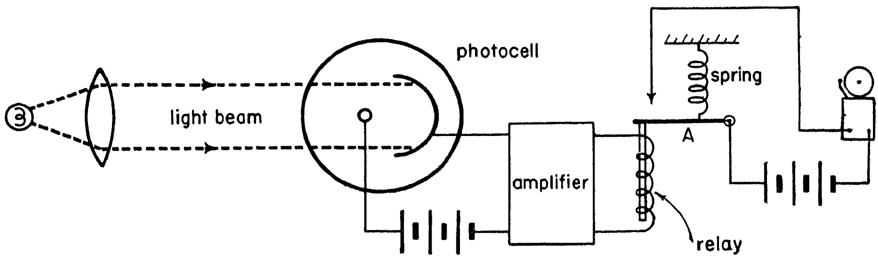


Fig. 363. Photocell-controlled alarm. When the light beam is interrupted, it stops current from the photocell and amplifier and through the relay coil. Thus the relay magnet releases the iron piece A, the spring pulls it upward and closes the electric-bell circuit.

by a relay when light is interrupted. Doors may be opened, drinking fountains turned on, motors started, etc. Street lights in many cities are now commanded to turn on automatically whenever the daylight grows dim. A short time ago, light which started from a distant star 100 years before was made to fall on a photocell and turn on the lights at a great exposition.

Automatic Control in Industry. Do you want something controlled? If so, the chances are that a photocell will do it best. Continually being developed are new automatic control devices which utilize photocells to do things both better and faster than man can do them. Photocells make fine inspectors. A photocell watching oranges, coffee beans, or paper sheets passing by on a conveyor belt can be arranged so that it does not interfere as long as the normal amount and color of light is reflected from the passing objects. But when a green or spoiled orange, a black coffee bean, or an off-color paper sheet passes, the photocell reacts immediately, sending current through a magnet which pulls a lever to throw out the defective object in a split second. The use of these more than human controls is increasing so rapidly that questions as to the future effect of almost completely automatic production systems are exceedingly important.

Sound and Light on Film. The motion picture industry alone uses more than a hundred thousand photocells. It is the photocell which in thousands of movie theaters transforms the gradations of shade in the "sound track" of a film to electric pulses and then

to sound. In the studio, the sound waves which originally strike the microphone are converted into electric pulses which in turn operate an apparatus that varies the amount of light falling on the narrow strip at the side of the "frames." The variations in area

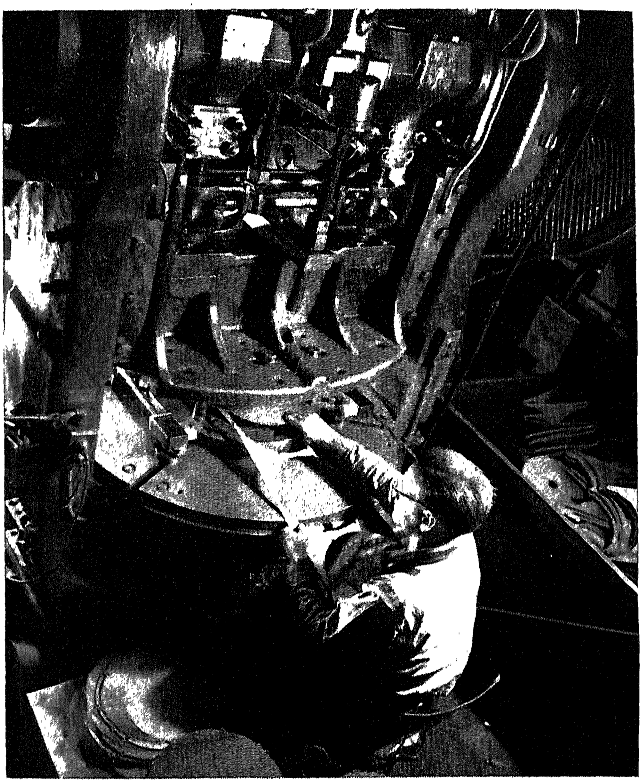


Fig. 364. Fingers of press operator protected by Westinghouse phototube relay. Operation is prevented when a light beam in front of the press is broken.

of the blackened part of the sound track thus correspond to the variations in the original sound. In the theater, light from a lamp is focused by lenses and sent through the sound track into a photocell. As the film moves steadily, the variations in the amount of light transmitted through the variably darkened area of the sound track in turn cause the tiny electric currents produced in the photocell to vary in the same manner. These currents are amplified enormously until they are powerful enough to force the coil of a loudspeaker to move back and forth. Thus the pushes and pulls of the

loud-speaker diaphragm on the air correspond to the air-pressure variations which originally operated the recording microphone. In

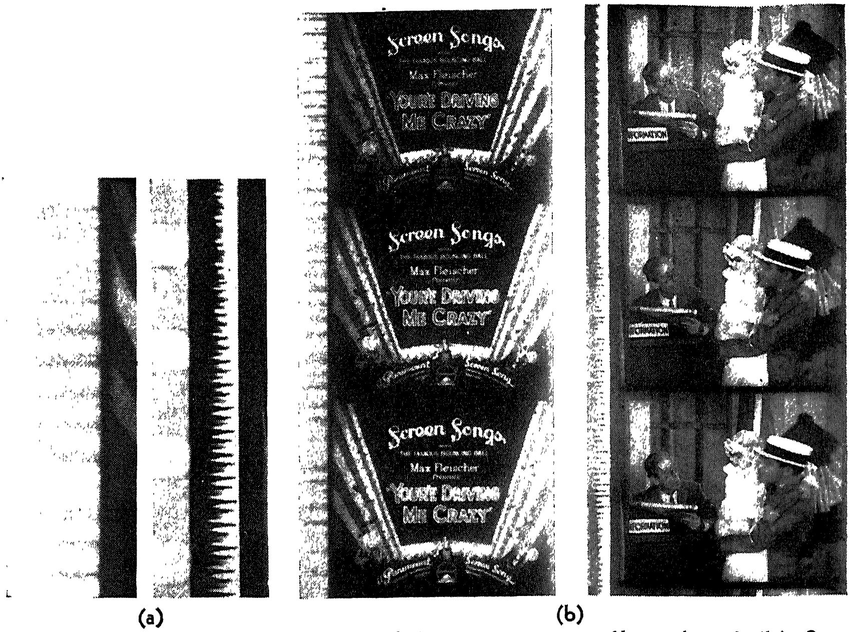


Fig. 365. (a) Short lengths of sound track from motion-picture film, enlarged. (b) Sound track is situated directly alongside of picture frames.

The variable density type of track (left) changes the intensity of the light which passes through it on the way to the photocell. The variable area type of track (right), now largely used, changes the area of the light beam. Both types of sound recording produce essentially the same effect, i.e., they control the rate at which light energy reaches the photocell of the reproducing system.

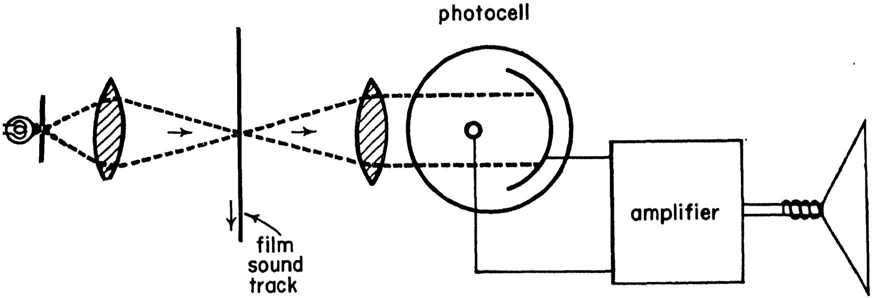


Fig. 366. Simplified diagram of system for reproducing sound from motion-picture film.

spite of the complexity of this process, physicists and engineers, particularly those in the larger organizations such as the Bell Telephone Laboratories and the Radio Corporation of America,

have through careful work developed the apparatus to such a stage that the reproduction of the original sound is almost perfect.

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SUMMARY

Leading to modern physics were the discoveries of ***X rays*** by Roentgen in 1895, of ***radioactivity*** by Becquerel in 1896, and of the ***electron*** by Thomson in 1897.

Flames, white-hot metals, X rays, and radioactive radiations produce positive and negative ions in air by detaching electrons from atoms. These ions tend to recombine rapidly.

Gases, ordinarily good insulators, become conductors when the ***potential gradient*** (volts/cm) becomes great enough (about 30,000 volts/cm for normal air).

The gas in a discharge tube is an insulator at high and very low pressures. At intermediate pressures it is a conductor, producing a luminous discharge. The latter is set up by cumulative ***ionization by impact***.

In a discharge tube at low pressure a greenish fluorescence of the glass walls is produced by rays from the ***cathode*** (***cathode rays***). These rays behave like identical negatively charged particles. From deflections of cathode-ray particles in electric and magnetic fields, J. J. Thomson measured the ratio (charge/mass) of each particle, or ***electron*** as it came to be known.

In 1910, Millikan measured the charge on an electron by observing how charged oil droplets fall when in an electric field. This charge, 1.6×10^{-20} coulomb, is so small that 6×10^{18} must flow

per second to equal 1 amp of current. The electron's mass, 9×10^{-28} gram, is 1/1,850 that of the hydrogen atom, and its effective size, about 10^{-13} cm, is about 1/100,000 that of the hydrogen atom.

In the cathode-ray tube a well-focused electron beam striking a fluorescent screen may be deflected at will by voltages applied to two pairs of electrodes which act at right angles to each other. Such tubes are useful to investigate high-speed electrical phenomena, to reconstruct the image in television receivers, and to study biological actions.

Magnetic fields in coils or electric fields in charged rings behave just like electron "lenses." Used in electron microscopes, they give images of objects 100 times smaller than ordinary microscopes can reveal.

Hallwachs first studied the ***photoelectric effect,*** in which light pulls electrons from metal surfaces, especially zinc or alkali metals. The number of ***photoelectrons*** emitted per second is proportional to the intensity of light. Contrary to the simple wave idea of light, no photoelectrons can be ejected, no matter how intense the light, unless the light frequency is sufficiently high.

This peculiarity was "explained" by Einstein, using Planck's idea that light comes in units called ***quanta,*** and that

$$\text{Energy of quantum} = h \times \text{frequency}$$

where h is a universal constant. If E_0 is the energy with which an electron is bound to a metal surface, it takes a quantum of energy greater than E_0/h to eject the electron.

In a ***photocell,*** photoelectrons are made to flow as a current, usually by an external battery.

The action of the eye, the formation of photographic images, and photosynthesis in plant life have as their bases chemical reactions controlled by photoelectric action.

Photocell controls are used for the operation of a great variety of automatic devices, for automatic inspection, and for the sound "pick-up" in sound films.

QUESTIONS

1. What did such experimenters as Thomson, Becquerel, Roentgen, and Hertz contribute to the modern era of physical science?
2. Is the current in a gas essentially different from that in a copper wire?
3. How can air be ionized?

4. How does an electric discharge in air change appearance as the pressure is reduced? What other change takes place?
5. How does ionization by electron impact account for the main characteristics of a gaseous discharge?
6. What are ***cathode rays?*** How were they identified as particles instead of waves?
7. How did J. J. Thomson measure the ratio of charge to mass of cathode-ray particles, or ***electrons?***
8. How did Millikan measure the charge on the electron?
9. What is the comparison between the charge and mass of an electron and of a hydrogen nucleus?
10. How does a modern cathode-ray tube function? What are its uses?
11. In a cathode-ray tube, why is an AC voltage of "saw-tooth" wave form often applied to the plates that produce horizontal deflection?
12. What are "electron lenses"? Of what practical use are they?
13. What experiments indicate a connection between light and electrical phenomena?
14. How do we know that particles ejected ***photoelectrically*** from materials really are electrons?
15. How does change of intensity of light influence the photoelectric effect?
16. In what way does photoelectric emission depend upon the frequency of the light used?
17. Why was the existence of a frequency ***threshold*** for the photoelectric effect difficult to explain on the assumption that light is an ordinary sort of wave motion? How did Einstein resolve this difficulty?
18. What is the characteristic of a ***quantum*** of light energy?
19. On page 469 it was stated that 100 quanta of visible light (average wave length 0.00005 cm) possess about 3×10^{-17} joule of energy. Is this statement true?
20. What is meant by a "photochemical reaction"? In what classes of phenomena are such reactions important?
21. What are some applications of photocells?

CHAPTER XVI

ELECTROMAGNETIC WAVES

HISTORY OF ELECTROMAGNETIC RADIATION

Prediction. In 1864, James Clerk Maxwell in England published some epoch-making articles on the nature of light and electricity and magnetism. Maxwell, fascinated by the experimental work of Faraday, undertook some theoretical calculations about it which led him step by step to the conclusion that light is an electrical and magnetic wave motion. His theory is too complex to deal with here, but essentially he concluded that vibrating electric charges should set up varying electric and magnetic force fields, called ***electromagnetic waves,*** which would travel through space with the velocity of light, 186,000 miles per second or 3×10^8 meters/sec.

Discovery. It was not until 1887, seven years after Maxwell's death, that Heinrich Hertz in Germany proved by direct experiment the existence of electromagnetic waves. Hertz discovered that when a spark was caused to jump the gap between two balls connected to charged plates, as in Fig. 367, tiny sparks would also jump between two close balls in a similar system, even if the second system were some distance away. From careful experiments he concluded that the energy was transferred to the second system by waves which could be reflected and refracted and made to interfere, and which behaved in general just like light waves except that their wave length was much longer.

Other investigators quickly started to study this new discovery, and a great variety of experiments showed that these were indeed electromagnetic waves, and that they verified Maxwell's brilliant theoretical deductions.

When electromagnetic waves are set up, what is happening may be roughly described as follows: If electric charges are forced to vibrate back and forth, as in alternating currents, then an alter-

nating magnetic field is created near the vibrating charges. This field first "points" in one direction, then decreases to zero, builds

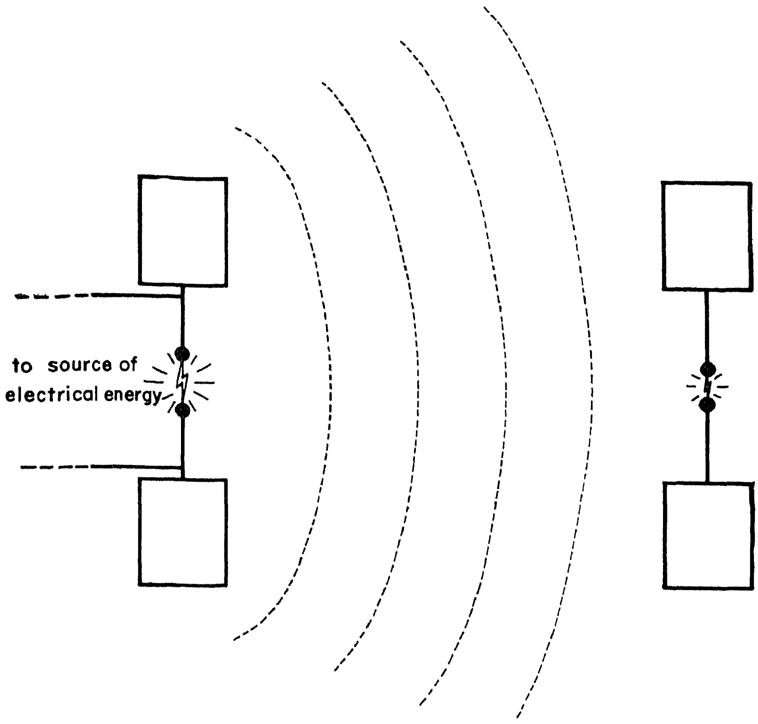


Fig. 367. Hertz obtained the first experimental evidence of electromagnetic waves. Radiation from an oscillating spark discharge in the left-hand circuit sets up sparks in the gap at the right.

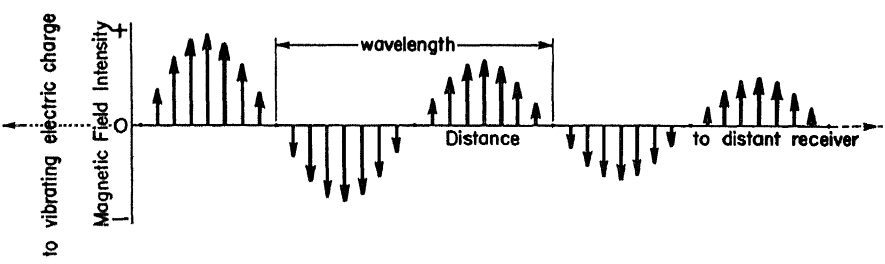


Fig. 368. Magnetic field associated with an electromagnetic wave that originated to the left. This is a "snapshot" representation of the magnetic field intensity along the path of the wave at a single instant.

up in the opposite direction, becomes zero again, etc. These changes occur with a frequency which equals the frequency of vibration of the charges, for whenever electric charges are moving (that is,

when there are electric currents) magnetic fields are produced which are proportional to the speed of the charges.

The magnetic or electrical disturbance produced travels outward, according to Maxwell, with a speed of 3×10^8 meters/sec.

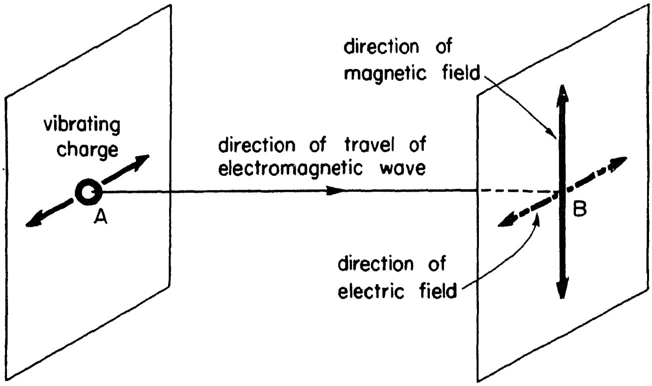


Fig. 369. Electromagnetic waves from the vibrating charge at A set up oscillating electric and magnetic fields in space which are perpendicular to one another, as indicated for the particular point B. The electric and magnetic fields travel together and have the same frequency, called the frequency of the electromagnetic wave.

Thus, at any instant the magnetic field strength in space would vary from point to point about as represented in Fig. 368.

Now whenever these spreading changing magnetic fields pass over a wire they induce a voltage in that wire, as Faraday discovered long ago in his experiments on electromagnetic induction. When the wire has the same length as the wave (or some half-multiple thereof), or whenever the circuits connected to the wire have a ***natural resonant frequency*** equal to the frequency of vibration of the original charge, there is an increased tendency to make the electric charges in the wire and its circuit vibrate back and forth at that same frequency.

Frequency, Wave Length, and Speed. The wave length and frequency of an electromagnetic wave are related by the same fundamental expression which applies to all wave motions. We recall (see page 255) that it is

$$\text{Speed} = \text{frequency} \times \text{wave length}$$

Wireless. Many men quickly saw that the possibility of transmitting electromagnetic energy over a distance, without wires, might lead to practical results. Attempts to make more and more

powerful sources of oscillation were pursued and likewise ever more sensitive detectors were developed. Many believed, of course, that such waves could never be transmitted farther than one could see because of the curvature of the earth.

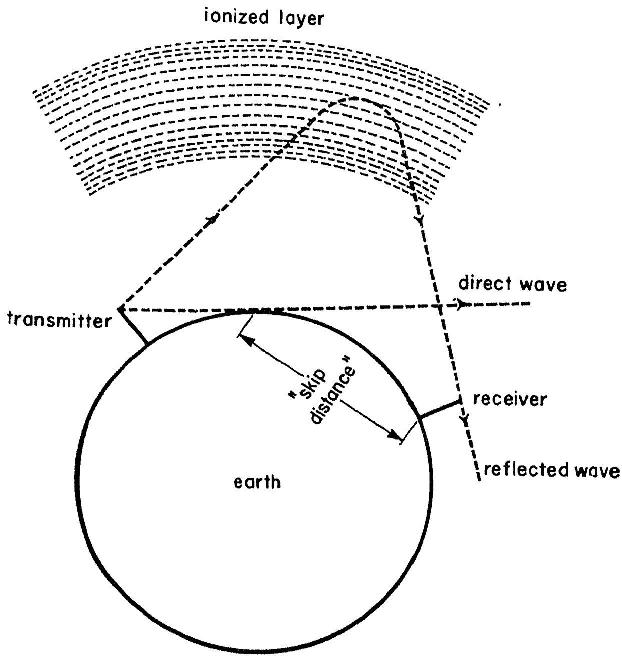


Fig. 370. Radio waves, which cannot reach a distant receiver directly because of the earth's curvature, may be reflected to it by the Kennelly-Heaviside "layer," an ionized region in the upper atmosphere. The distance between the earth's surface and the ionized reflecting region is greatly exaggerated on the scale to which the earth is drawn. This distance on the diagram actually should be about 1 mm.

G. Marconi in 1896 was probably the first to demonstrate that Hertzian waves could be used for practical distant communication. Marconi showed that such waves could be detected at very great distances, far beyond what the curvature of the earth would lead one to expect, and in fact that very long waves, especially those 200 to 10,000 meters in length, seemed to follow the curvature of the earth. This was rapidly applied over increasing distances to telegraphic transmission by "dots and dashes," as Marconi's inventive genius proved a match for the many difficulties which arose. In 1901, Marconi demonstrated that signals sent from England could bridge the Atlantic and be picked up in Newfoundland.

Later investigations showed that the direct wave actually did not go much beyond the shadow produced by the earth's curvature. Fortunately, however, there is an ionized reflecting region, the so-called Kennelly-Heaviside layer, in the upper atmosphere 50 to 150 miles above the earth. This ionization is caused largely by the effects of the sun's radiation in the rarefied gases at such great altitudes. Several distinct strata have been observed in this ionized region which effectively reflect and refract the waves back to the earth so that they can be detected at very great distances. The reflecting layer is not usually effective for waves less than ten meters in length, and its variable height produces peculiar effects such as fading and marked differences between night and day reception. The electric charges projected toward the earth during sunspot activity affect the layer markedly and thus cause queer changes in radio reception.

The new mode of signal transmission worked increasingly well as developments by many workers followed Marconi's initial trials. A new era in communication had begun. Ships at sea, isolated regions, in fact all parts of the world could be linked together by this new discovery.

NEW PHENOMENA WITH CHANGING ELECTRIC CURRENTS

Many new phenomena occur as the result of ***changes*** in electric currents. We shall need to consider these effects before we can intelligently appreciate radio, television, and the other great devices for communication.

Inductance. When current is set up in a closed electric circuit, say by connecting a battery to it, we are accustomed to say that the amount of current is determined by the resistance of the conductors and by the potential difference of the battery. According to Ohm's law, the current I is given just by the relation V/R, where R is the ordinary resistance.

Now this is not the whole story, for, while Ohm's law is correct if we wait until the current reaches its final steady value, it is not correct ***immediately*** after we close the switch in the simple circuit ***because it takes time for a current to build up to its final value.***

All electric circuits have a characteristic, called ***inductance,*** which is very closely analogous to mechanical inertia, or mass.

Such inertia effects are observed most easily with coils of wire, particularly if wound on iron cores.

Suppose that we connect a large coil of wire wound on a core of iron, in other words a large electromagnet, into a circuit contain-

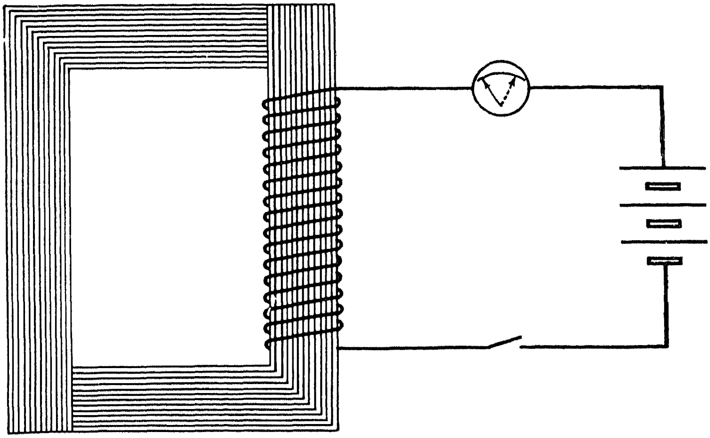


Fig. 371. Large iron-core inductance in series with a battery, current meter, and switch.

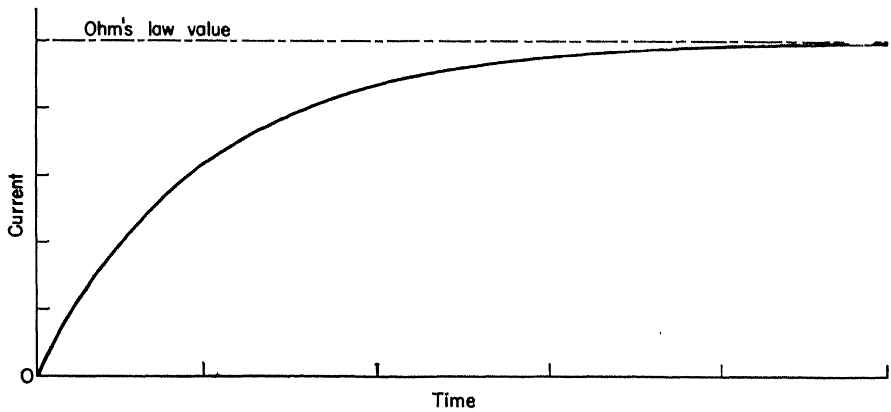


Fig. 372. Growth of current in an inductance coil when a DC voltage is suddenly applied. The final value (dot-dash line) is just the ratio of the voltage to the resistance of the coil and the remainder of the circuit. The time scale (horizontal) for this diagram depends upon the value of the inductance and resistance; that is, the fractional rise of current is slower the greater the inductance and the smaller the resistance.

ing a battery, a switch, and a fast-acting ammeter to measure the current (Fig. 371). If we close the switch suddenly, we see that the ammeter pointer moves up very slowly and may take many seconds to reach its final value—far longer than could be ac-

counted for by the mechanical inertia of the meter. Of course, the ammeter coil itself does have inertia. Accurate studies require an "inertialess" indicator such as an electron beam "writing" on the screen of a cathode-ray tube. If such a very rapidly acting device is

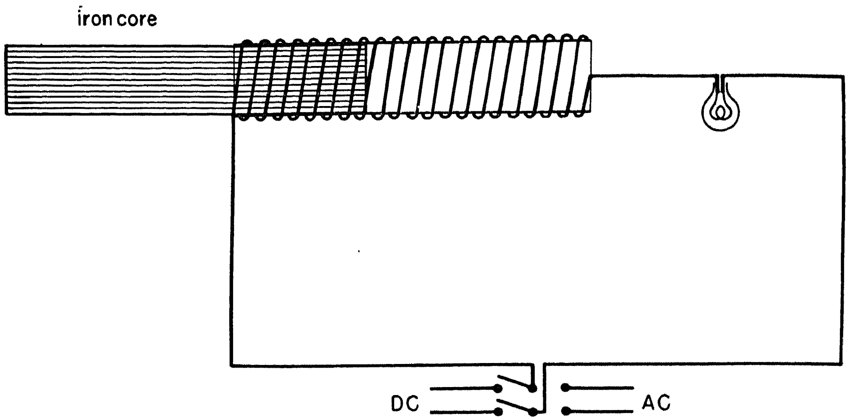


Fig. 373. Variable inductance to which either AC or DC voltage can be applied. Iron core is retractable.

used to study the growth of current with time, the result looks about like Fig. 372. The current is seen to start at zero, rise fairly rapidly at first, and then gradually approach the final steady value which Ohm's law would give us from the total electric resistance of the circuit and the battery voltage. The peculiar form of the current growth curve is what is called an "exponential" curve.

This electrical inertia effect we say is caused by the ***inductance*** of the coil. As might be expected, the inductance increases with the number of turns of wire in the coil and varies with the amount, type, and arrangement of iron in the core. With no iron, the inductance of a coil is much reduced. However, even a straight piece of wire has some inductance, and it takes time, even if an exceedingly short time, for the current to build up in any circuit.

Effect of Inductance on Alternating Current and Direct Current. It is interesting to compare the effects of direct and alternating current when connected to a coil with an iron core. The difference is seen immediately if a lamp is put in series with the inductance (Fig. 373). When connected to a steady direct-current source, the lamp becomes bright fairly soon, showing that in time there is

full current and that the inductance of the coil has only a momentary effect. If, however, a comparable alternating voltage is used, the lamp will glow either dimly or not at all when the iron core is inside the coil. In this case, the current builds up so slowly because

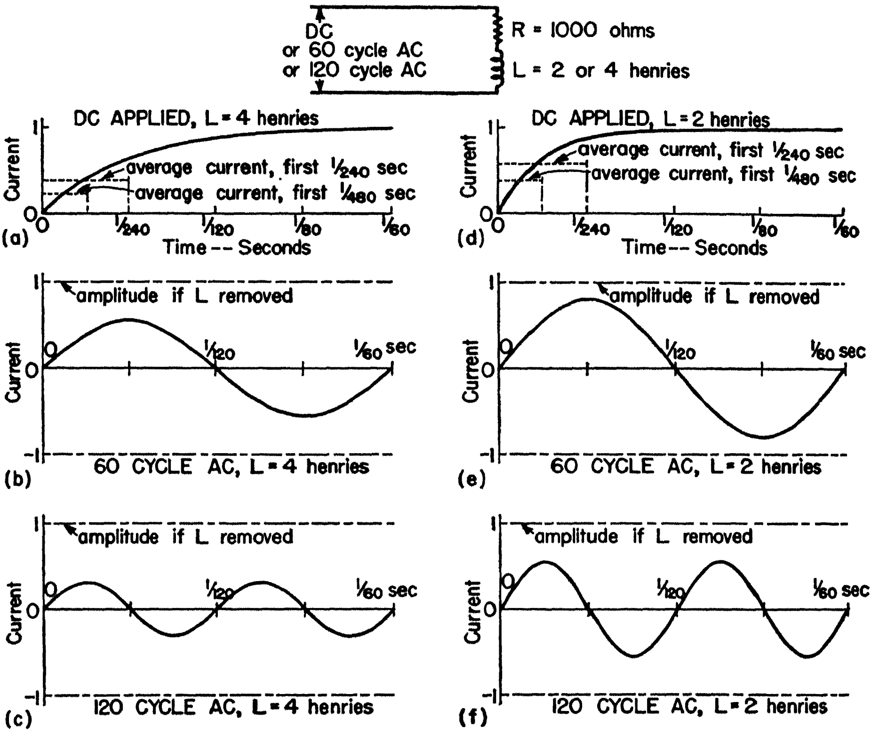


Fig. 374. Effect of inductance value and of AC frequency on the current in an inductance coil. The larger the inductance, the smaller the AC current (compare b and e, or c and f). This seems plausible from the DC growth curves (a and d), for in $\frac{1}{240}$ sec, which is the time for 60-cycle AC to build up from zero to its maximum voltage value, the current rises to a higher value in the smaller inductance than in the other.
The higher the frequency, the smaller the AC current in the inductance coil (compare b and c, or e and f). Again, the DC growth curves make this seem reasonable, for the higher frequency allows less time for current buildup in each cycle; hence the peak current is less than for the lower frequency AC.

of the large inductance of the coil, that the alternating voltage reverses before the current has a chance to build up very far. If, now, the iron core is withdrawn progressively from the coil, the lamp glows steadily brighter, and when the core is removed the lamp glows with approximately the same brilliance on alternating current as on direct current.

Such devices, called ***variable inductances,*** or ***variable reactors,*** are used widely to control currents in AC circuits, for example, to dim the lights in theaters. Variable resistances (rheostats) of course would also work in AC circuits, and, indeed, there is no choice but to use them in DC circuits, where inductances have no lasting effect. However, for AC circuits, inductances are much more efficient than resistances, because the latter always have energy losses which waste electricity to produce heat (I^2R watts). The heat loss in an inductance is small because its actual resistance is usually low.

Inductance, then, as well as resistance, limits the magnitude of an alternating current, or, more generally, inductance opposes ***changes*** in current. The larger the inductance, the greater is its influence on alternating current, and, as might be expected, it has more effect on a high-frequency than a low-frequency current. The reason that inductance behaves as it does is simply this: When a current starts to change, the magnetic field that is produced around the current starts to change. Now, as we learned, Faraday discovered that changing magnetic fields can induce voltages in wires. Thus, the changing magnetic field which is caused by a changing current in a wire in turn ***induces a voltage back into the same wire.*** This induced voltage is such that it ***opposes*** the initial change in current.

Inductance, usually designated by the letter L, is measured in ***henrys,*** named in honor of Joseph Henry, an American who first performed many of the experiments with coils of wire and electromagnets. If the current in a coil is changing at the rate of one ampere per second and the induced voltage is one volt, we say that the inductance of the coil is one henry.

Magnetic potential energy is stored by an inductance coil in which there is current; there is, in fact, energy in the magnetic field around any coil or wire carrying a current. As with all potential energy, work must be done to store this energy, that is, to create the magnetic field.

Capacitance. In Leyden, an early experimenter with electrostatic machines discovered quite accidentally that a glass jar could "store" electric energy if it had conducting material on its inside and outside (Fig. 375). When a "Leyden jar" is charged by touching the inner conductor to the high-voltage terminal of a "static"

machine, energy is stored, and even a long time afterward a large spark will jump if the two ends of a conductor are brought near the inner and outer coatings.

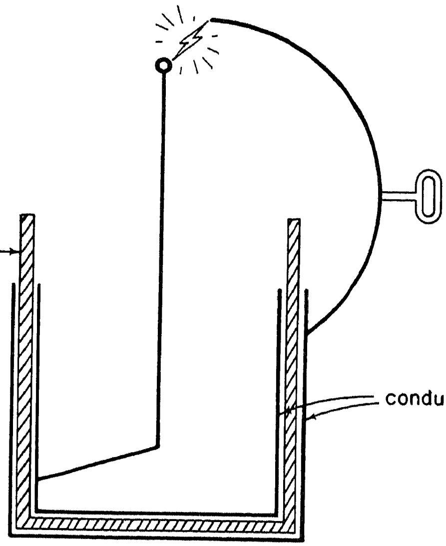


Fig. 375. Electrical energy can be stored in a "Leyden Jar" (an early form of condenser). After charging by applying a voltage between the two foils, a spark can be made to jump between conducting wires which touch the two foils.

Condensers. Two electric conductors separated by an insulating medium, as in a Leyden jar, are commonly called *condensers*. We learned earlier that if one conductor is charged electrically it will induce an opposite charge on a neighboring conductor that is insulated from it. Electric energy is stored in the region between the two oppositely charged conductors because an electric field exists there and forces will be exerted on any electrically charged object brought into the region. We say that such a device which stores electric potential energy has *capacitance*. Actu-

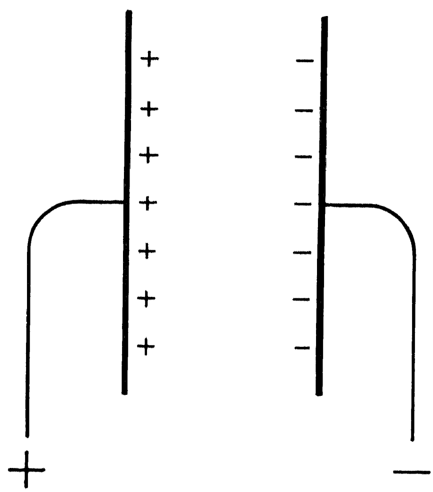


Fig. 376. A condenser stores electric charge.

ally, any single conductor also has capacitance, for there is always earth, if not other near-by objects, on which charges are induced when the conductor itself is charged.

Dielectric. The medium between the two conductors, in which

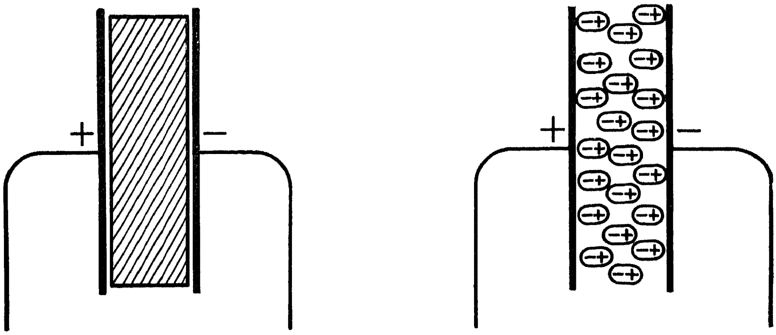


Fig. 377. Dielectric material between the plates of a condenser increases the electrical energy that is stored when a given voltage is applied, e.g., the additional energy may be potential energy of deformation of the atoms or molecules, set up by attraction of negative charges in the dielectric toward the positive plate and positive charges toward the negative plate.

the electric energy is stored, is called the ***dielectric.*** When materials such as glass, paper, mica, oil, or other good insulators are placed between the plates of a condenser, much more energy may be stored than if the plates are separated by air or vacuum. The atoms and molecules of these insulators are made of electric charges, so when the plates are charged the negative charges in the dielectric (electrons) are attracted toward the positive plate, while the positive charges are attracted toward the negative plate. The atoms are in effect ***elastically deformed.*** Producing this electrical deformation is much like stretching a spring or pumping gas under pressure into a container—in each case considerable energy can be stored. As the voltage between the plates is increased, the energy of deformation, and consequently the stored energy, is increased. Of course, if the voltage is too high, the strain is so great that the atoms become disrupted, the dielectric is punctured, and the condenser discharges.

Properties of Condensers. The capacitance of a condenser is usually calculated in ***farads,***[1] named in honor of Michael Faraday.

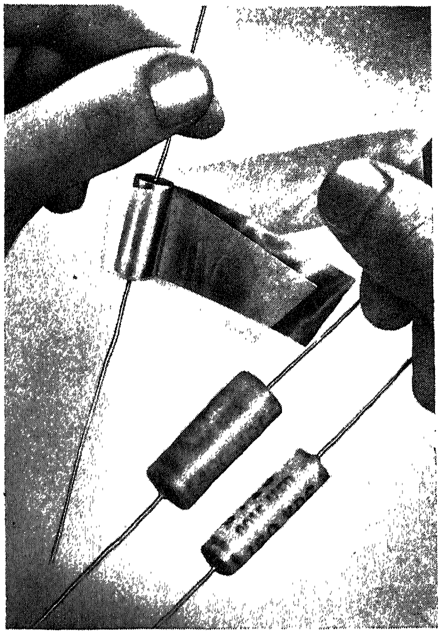
[1] The farad is such a large unit of capacitance that condensers usually range from about 10^{-11} farad to 10^{-5} farad. For this reason the microfarad (10^{-6} farad) is often used as the capacitance unit.

As we might expect, the capacitance of a parallel plate condenser is proportional to the ***area*** of a plate, inversely proportional to the ***distance*** between the plates, and also depends upon the type of dielectric. In mathematical form, then, if we include a constant which makes the units come out right, we have:

$$\text{Capacitance} = \frac{8.8 \times 10^{-14}\,(\text{area of plate})K}{\text{distance of separation}}$$

Here K is called the ***dielectric constant.*** If capacitance is in farads, area in square centimeters, and distance in centimeters, K is 1 for air and may be as high as 2 to 7 for other materials such as glass, mica, or oils.

Condensers are reservoirs for electricity. They may be likened to water storage tanks, or better still to gas storage tanks. Gas may be fed into a tank (up to the bursting point) simply by using a compressor to pump the gas into the tank under higher and higher pressure, thus storing more and more potential energy. The volume of the gas tank is analogous to the capacitance of a condenser; the total mass of gas pumped in corresponds to the total electric charge (of either sign) forced into the condenser; and the pressure in the gas tank corresponds to the voltage between the plates of the condenser. For a condenser



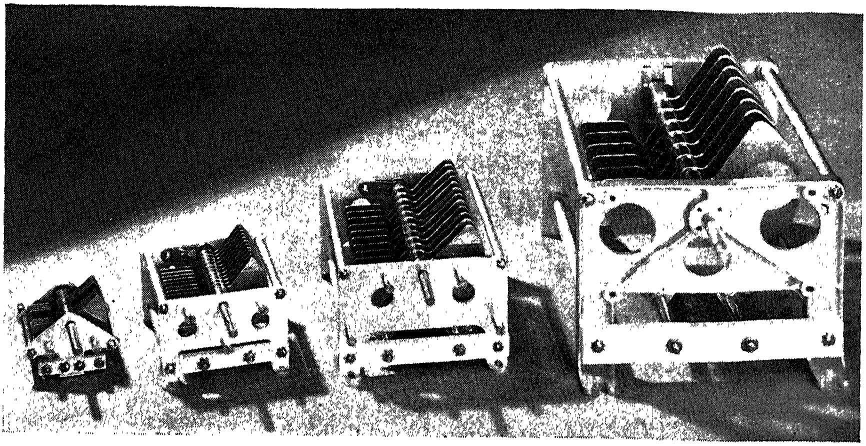
(Bakelite Corporation.)

Fig. 378. Fixed condensers with polystyrene film as a dielectric between metal foils rolled up into compact form.

$$\text{Total charge of one sign} = \text{capacitance} \times \text{voltage}^1$$

Many kinds of condensers are in use today. Where high capacitance is required, two long sheets of tinfoil separated by special thin paper impregnated with oil or wax may be rolled up into a

[1] Charge is usually expressed in coulombs, capacitance in farads, and potential difference in volts.



(National Company.)

Fig. 379. Variable air condensers for operation at various voltages.

small space. Extremely thin oxide layers on the electrodes serve as the insulating dielectric in the compact so-called "electrolytic" condensers. When high voltages must be withstood, mica serves well as a dielectric because it strongly resists puncture. ***Variable condensers*** of small capacitance, which are used widely for radio tuning, consist of two sets of approximately semicircular insulated plates which may be enmeshed to any desired extent.

Effects of Capacitance on Direct and Alternating Current. It is important for us to see how condensers behave on direct and

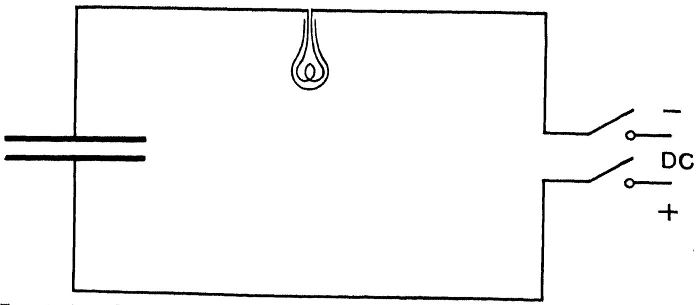


Fig. 380. Condenser and lamp in series, to which a DC voltage may be applied.

alternating currents. If a large condenser in series with a lamp is connected suddenly to a steady voltage source, the lamp flashes suddenly and then goes out (Fig. 380). Subsequent opening and closing of the switch does nothing. There is a ***momentary*** current to charge the condenser, but after the charging is complete no

current remains. If the terminals of the condenser are brought near one another, the electric energy that has been stored discharges with a large spark.

A cathode-ray tube shows that the current is high when the

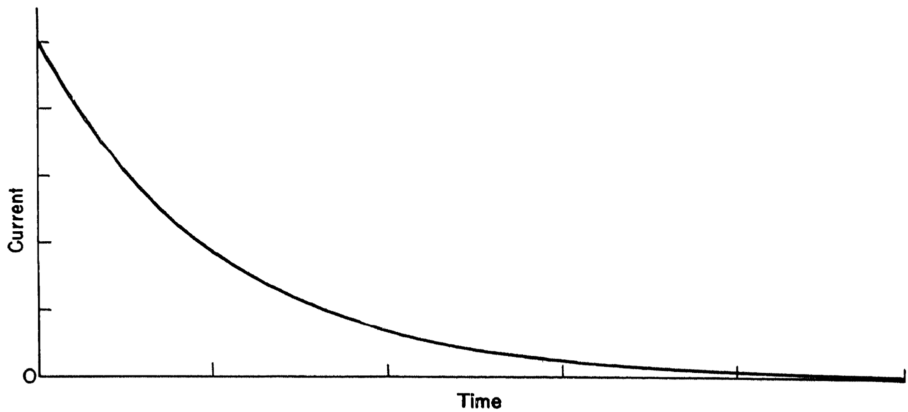


Fig. 381. Decay of current when DC voltage charges a condenser through a resistance (resistance of lamp filament, wires, etc. in Fig. 380). The time scale (horizontal scale) is determined by the value of the capacitance and the resistance; that is, the fractional current decreases more slowly the greater the capacitance and resistance values.

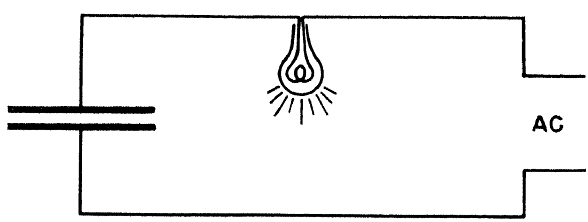


Fig. 382. AC voltage sets up current in a condenser.

switch is first thrown and then decreases rapidly to zero, as in Fig. 381. This is exactly opposite to what happened with the inductance, Fig. 372, where the current was zero at first and then increased to its final value.

When connected to an alternating voltage source, however, the lamp in series with the condenser appears to glow steadily. There is a current in the condenser, first in one direction to charge it, and then in the opposite direction to charge it oppositely, and so, if the frequency of the reversals is high enough, the charging currents are always appreciable, and the lamp glows with a steady brilliance.

These experiments show clearly that alternating currents "pass through" condensers. The larger the condensers, the larger the

current for a given voltage. Likewise, the higher the frequency of the alternations, the less time there is for the charging currents to die down, and the greater the effective current. Again, this is just opposite to the behavior of inductance coils.

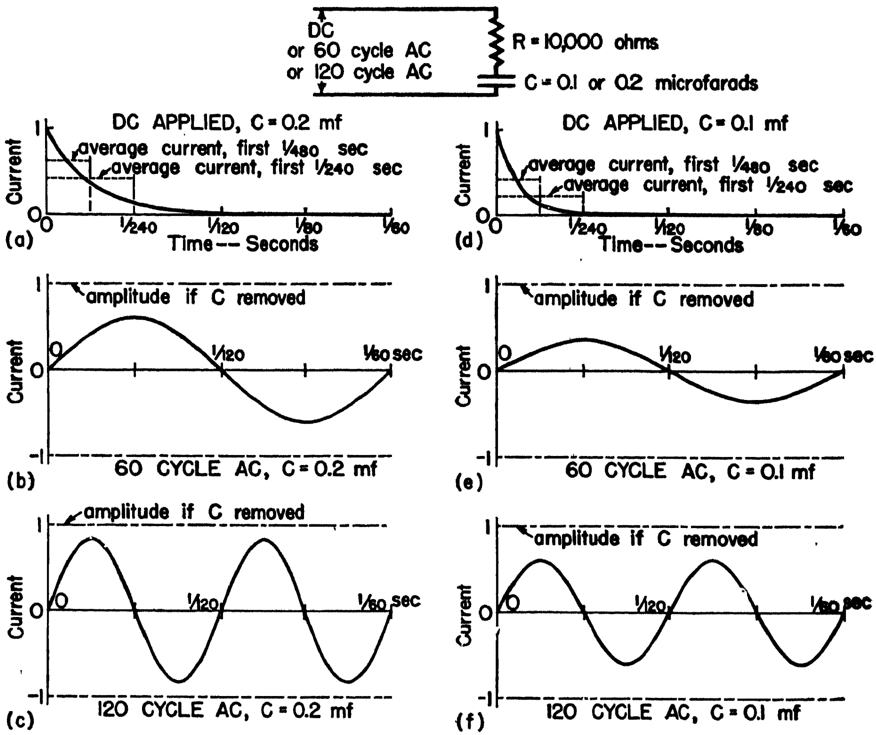


Fig. 383. Effect of capacitance value and of AC frequency on the current in a condenser and resistance. The smaller the capacitance, the smaller the AC current (compare b and e, or c and f). Comparison of the DC decay curves (a and d) makes this seem reasonable, for during 1/240 sec (the time for 60-cycle AC to drop from maximum voltage to zero) the average current is greater for the larger capacitance than for the other.
The higher the frequency, the greater the AC current in the condenser (compare b and c, or e and f). The DC decay curves make this plausible, for the higher frequency allows less time for current decay in each cycle, hence maintains the average current at a higher value than does the lower frequency AC.

Electric Oscillations. Earlier we saw that when a mass M on an elastic spring is pulled down beyond its normal position and released, the potential energy in the stretched spring is converted rapidly to the kinetic energy of motion of the mass. Because of its inertia, the mass overshoots the equilibrium point and goes beyond it until its kinetic energy changes once more to potential energy.

The mass oscillates up and down with decreasing amplitude until frictional forces finally bring it to rest. The frequency of the oscillation is given by a simple relation,

$$\text{Frequency} = \frac{1}{2\pi\sqrt{\text{mass} \times \dfrac{1}{\text{elastic constant of spring}}}}$$

In electric circuits, we have seen that the ***inductance*** of a coil is essentially the same as electrical inertia and so is analogous to mechanical mass. On the other hand, the effect of capacitance is essentially similar to electrical elasticity and thus corresponds to something related to mechanical elasticity as typified by a spring or by gas in a container (an air cushion, for example, is obviously elastic)—the value of capacitance actually is analogous to the ***inverse*** of a mechanical elastic constant. The reason is that increasing a capacitance is similar to increasing the volume of a gas container or ***decreasing*** the elasticity (force/displacement) of the gas in the container.

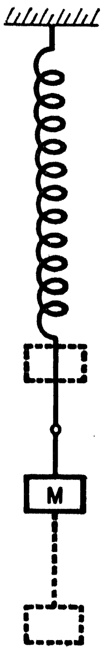
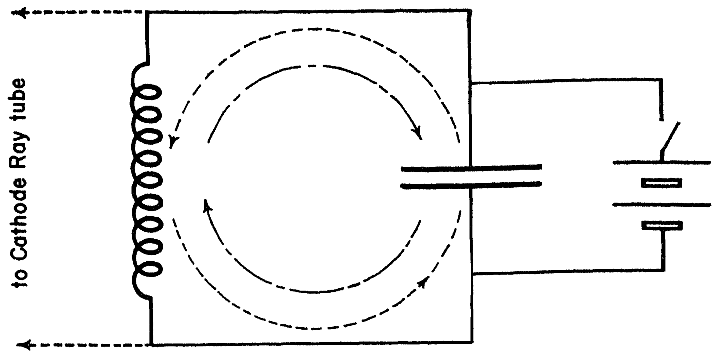
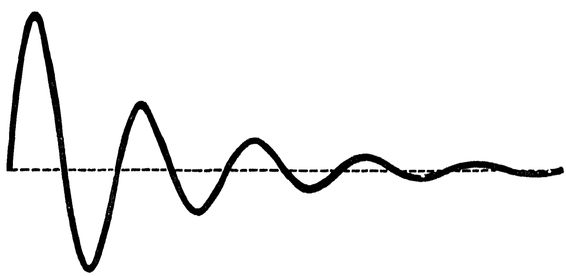


Fig. 384. Vibrations of a mass on the end of a spring are in many ways similar to natural electrical oscillations in a circuit.

As there are such close analogies between these electrical and mechanical properties, it is interesting to connect an inductance and a condenser together and see whether they behave in any way similar to the mass and spring. A cathode-ray tube will tell the story. First we charge the condenser (Fig. 385a) by closing the switch. (This is analogous to pulling the spring and the mass M down in the mechanical case.) Then, if the switch is opened, one plate of the condenser starts to discharge, so there is a current (negative electron flow) through the inductance toward the opposite plate. Once a current is started in the inductance, it cannot stop immediately because of the electrical inertia. It therefore "overshoots," and in effect gives a negative charge to the condenser plate that formerly was positive. The charge then surges back, again "overshoots," and so continues to oscillate back and forth until finally the loss of energy by electric friction, or resistance, "damps out" the oscillation (Fig. 385b).

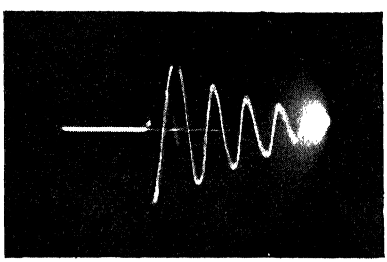


(a)

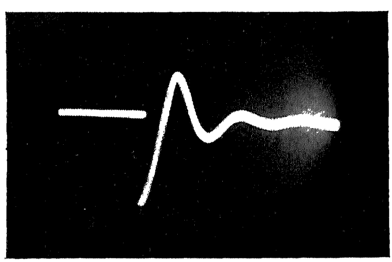


(b)

Fig. 385. (a) Circuit in which electrical oscillations have been set up. The charged condenser was allowed to discharge through the inductance, the electrical "inertia" of which causes the discharging current to continue too long, charging the condenser oppositely, so that the condenser must again discharge, etc. (b) Oscillograph record of the oscillating voltage across the inductance coil and condenser shown in (a). The greater the resistance in the circuit (chiefly in the inductance coil in this case), the more rapidly the oscillations die down. Note that the time for each successive oscillation is the same, but the amplitude decreases.



(a)



(b)

(*Radio Corporation of America.*)

Fig. 386. Photographs of oscillograph patterns of "damped" electrical oscillations. The circuits of (a) and (b) differ only in that the resistance is greater for (b) than for (a).

Thus, electric oscillations take place when energy is given to circuits containing inductance and capacitance, in a manner exactly analagous to mechanical vibrations in systems containing mass and elasticity. In fact, the frequency of vibration is given by

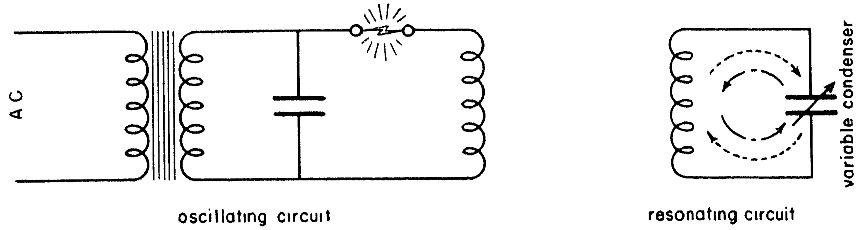


Fig. 387. Spark discharges in an oscillating circuit send out electromagnetic waves which can set up electrical oscillations in another circuit. The two circuits should be "tuned" to the same frequency for greatest effect.

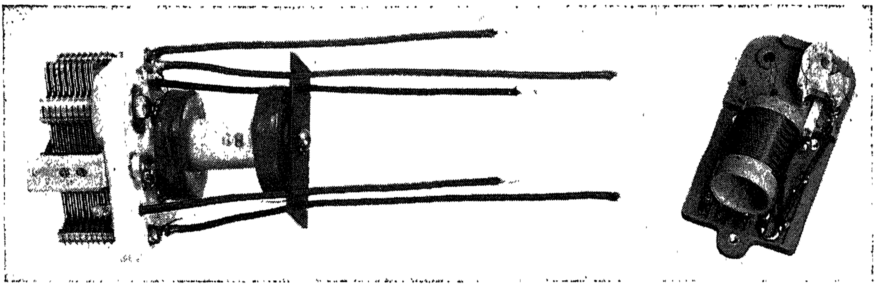
the same relation if mass and the inverse of the elastic constant in the mechanical case are replaced by inductance and capacitance, respectively, for the electrical case. This gives[1]

$$\text{Frequency} = \frac{1}{2\pi\sqrt{\text{inductance} \times \text{capacitance}}}$$

Every electric circuit, therefore, has a natural frequency of oscillation which depends only on the product of the effective inductance and the effective capacitance. Any desired frequency can be produced by using the proper amount of inductance and of capacitance. This is one of the most important principles in our communications developments, and it is particularly important in radio "tuning." It should be noted that increasing either the size of coil (inductance) or size of condenser (capacitance) decreases the frequency, while decreasing either increases the frequency.

Electrical Tuning—Resonance. Any two electric circuits will have the same natural frequency as long as the ***product*** of the inductance and capacitance is the same. We say that they are then ***tuned*** to the same frequency, or that they ***resonate*** at the same frequency. This can be shown strikingly by the apparatus indicated in Fig. 387, which is very much like the early radio "spark transmitters." Continually recurrent oscillation can be maintained in the inductance and capacitance of the left circuit by connecting a spark gap in series with the coil and condenser. When the condenser is charged

[1] The frequency is in cycles per second if the inductance is in henrys and the capacitance is in farads.



(*National Company.*)

Fig. 388. Two types of inductance coils mounted with variable condensers for tuning.

almost to the peak value of the high alternating voltage of the transformer, the spark gap breaks down, and oscillating currents surge back and forth in the condenser and inductance. On the next half-cycle, another discharge occurs, and so a series of powerful damped oscillations is produced. The frequency of these oscillations is determined by the size of the coil and condenser.

If a second coil and condenser are near by, some of the electric energy from the spark circuit is absorbed by this combination. If the variable condenser in the second circuit is tuned correctly, so that the product of its effective capacitance and the inductance in series with it is the same as in the spark circuit, the two circuits resonate with one another. Strong oscillations thus build up in the second circuit. If the spark circuit is powerful, and particularly if large inductance and small capacitance are used in the receiving circuit, large discharges will occur from a needle-sharp point attached to the second circuit when both circuits are ***tuned to resonance.***

The principles of tuning were first elaborated clearly by Lodge and Pupin, although the general idea was to some extent understood earlier. After becoming familiar with electron tubes, we shall see how some of these electromagnetic phenomena have been utilized.

FOR STUDY AND READING

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SUMMARY

In 1864, Maxwell predicted that vibrating electric charges should produce ***electromagnetic waves.*** In 1887, Hertz discovered such waves through their ability to induce voltage in conductors. This suggested the transportation of energy through space.

In 1901, Marconi sent wireless signals across the Atlantic. As this was beyond reach of the direct "beam," only waves reflected from the ionized upper atmosphere reached the receiver.

Inductance opposes ***changes*** in current (so it is the electrical analogue of inertia or mass). The inductance of a wire is increased by coiling the wire and by inserting an iron core. Inductance affects only ***changes*** in direct current, the steady value being set by Ohm's law; however, it limits alternating current to below the Ohm's-law value because alternating current ***changes*** continually. The larger the inductance and the higher the frequency, the greater is the ***limiting*** effect on alternating current. The inductance unit is the ***henry.*** Magnetic potential energy is stored in the field surrounding current in an inductance.

A simple ***condenser*** is two conductors insulated from one another; so a voltage puts equal and opposite charges on the conductors. Electric potential energy is stored in the field in a condenser, and this energy is increased by an insulating material or ***dielectric*** between the plates. ***Capacitance*** is the ability to store electric potential energy, and for a parallel plate condenser it is proportional to

$$K \times \frac{\text{area of a plate}}{\text{distance between plates}}$$

where K is 1 for vacuum and greater for material dielectrics. The unit of capacitance is the ***farad.*** In a condenser

$$\text{Total charge of one sign} = \text{capacitance} \times \text{voltage}$$

A condenser on DC has current only until the charging is complete. On AC, however, the voltages and hence the charges on a condenser are constantly being reversed, so there is always charging current. The larger the capacitance and the higher the frequency, the ***larger*** the AC current to a condenser.

When capacitance (analogous to 1/mechanical elasticity) and inductance (analogous to inertia or mass) are in the same circuit,

electric oscillations may be set up in the circuit (analogous to vibrations of a mass on an elastic spring). The frequency of these oscillations is

$$\frac{1}{2\pi\sqrt{\text{inductance} \times \text{capacitance}}}$$

This gives the natural frequency of any electric circuit in terms of its effective inductance and capacitance. Any two circuits with the same natural frequency (the same value of capacitance $\times$ inductance) can ***resonate,*** that is, oscillations in one of the circuits can induce relatively great voltages into the other circuit.

QUESTIONS

1. What historical background was there for Maxwell's prediction of ***electromagnetic waves?***
2. How was the existence of electromagnetic waves first verified experimentally?
3. How can charges set up electromagnetic waves?
4. Why is ***inductance*** sometimes called "electrical inertia"?
5. How may the inductance of a straight piece of wire be increased?
6. Is there any reason why a strong electromagnet should have a large inductance?
7. What is the effect of inductance on direct current?
8. Why is the influence of inductance on alternating current different from its influence on direct current?
9. What happens to the alternating current in an inductance when the frequency is increased without changing the value of the voltage across the inductance?
10. Why is the name "Joseph Henry" associated with inductance effects?
11. How does a ***condenser*** "store" energy?
12. Why is ***capacitance*** sometimes said to be analogous to the inverse of a mechanical elastic constant?
13. What is a ***dielectric?*** How can it influence the amount of energy stored in a condenser?
14. Upon what quantities does the capacitance of a parallel plate condenser depend?
15. How is the charge on a condenser related to the capacitance and voltage?
16. Each plate of a parallel plate condenser has an area of 100 cm^2 and the separation is 1 mm. What is the capacitance if the dielectric is air? If the dielectric is glass with a dielectric constant of 7? What is the charge in the latter case when 1000 volts are applied?
17. In what way does the effect of a condenser on alternating current differ from that on direct current?
18. How does an increase of capacitance change the current in a condenser when the alternating voltage on it is held constant? What is the effect of an increase in AC frequency?
19. What is the natural frequency of an electric circuit in terms of the inductance and capacitance?
20. What is the resonant frequency of a simple circuit which has an inductance of 0.1 millihenry (0.1×10^{-3} henry) and a capacitance of 0.01 microfarad (0.01×10^{-6} farad)?
21. What inductance must be connected to a capacitance of 1 microfarad to resonate at 60 cycles/sec?
22. Does every electric circuit have a natural frequency of oscillation?
23. What is meant by ***resonance*** of electric circuits?

CHAPTER XVII

ELECTRON TUBES—RADIO—TELEVISION

Heat and Electrons. That flames and red-hot pokers would discharge electroscopes was known 200 years ago. The investigators of that time, however, could not guess that the analysis of this effect would be long delayed and that it would lead ultimately to some of the most important electrical developments of the twentieth century.

In 1883, while perfecting his newly invented incandescent lamp, Thomas A. Edison discovered an interesting phenomenon which later became the basis for one of today's most useful devices—the vacuum tube. The life of the early carbon filament lamp was fairly short, and the bulbs soon became blackened, weakening the already feeble light. Now we know that the blackening of that type of lamp as well as that of the more modern tungsten lamp is due simply to evaporation of the atoms of filament material. To study what was happening, Edison placed a small metal plate in the side of the lamp, and was surprised to find that when the plate was connected to the positive side of the DC line through a galvanometer there was a small current between the hot filament and the plate. When the plate was connected to the negative terminal, nothing happened. This phenomenon was called the "Edison effect," but because it had no obvious use it was almost forgotten.

In 1896, when Sir J. J. Thomson discovered that one of the main current carriers in gas discharges is what we now call the ***electron,*** it became clear that Edison's phenomenon had to do with electrons liberated from the incandescent filament. Almost immediately, many workers began to experiment with thermally produced ions, or with ***thermionic*** effects.

The atoms of all materials contain ***electrons.*** When the temperature is raised high enough, some of the electrons ***evaporate*** from the material much as water molecules evaporate from the

surface of boiling water (or as the atoms evaporate from incandescent lamp filaments); just as in ordinary evaporation, the electrons must be given a considerable amount of energy before they can escape from their parent atoms. The number of electrons evaporated each second increases very rapidly with temperature

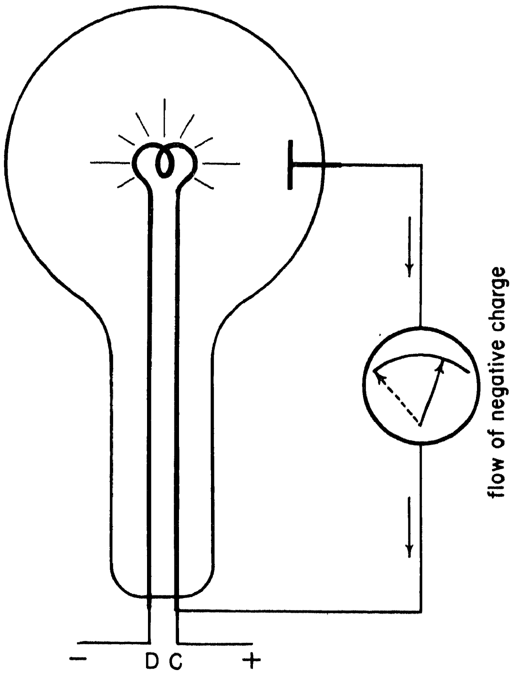


Fig. 389. The "Edison effect." There is a current in a conductor which connects a metal plate inserted in an incandescent lamp to the positive terminal of the lamp filament.

for pure materials, and it also depends on the nature of the material. Tungsten with its high melting point was found to be a very suitable electron emitter when at white heat.

Later investigators discovered that composite metal surfaces, made by adding some thorium to tungsten or, better still, by coating the surface of metals like nickel with a mixture of barium and strontium oxides, would give a very high electron emission even at dull-red heat. These coated filaments are employed widely in small radio tubes, although tungsten filaments are still used for the larger tubes.

THE TWO-ELEMENT TUBE OR DIODE

It is desirable to understand more about the behavior of thermionic emission. If, in an evacuated bulb containing a tungsten

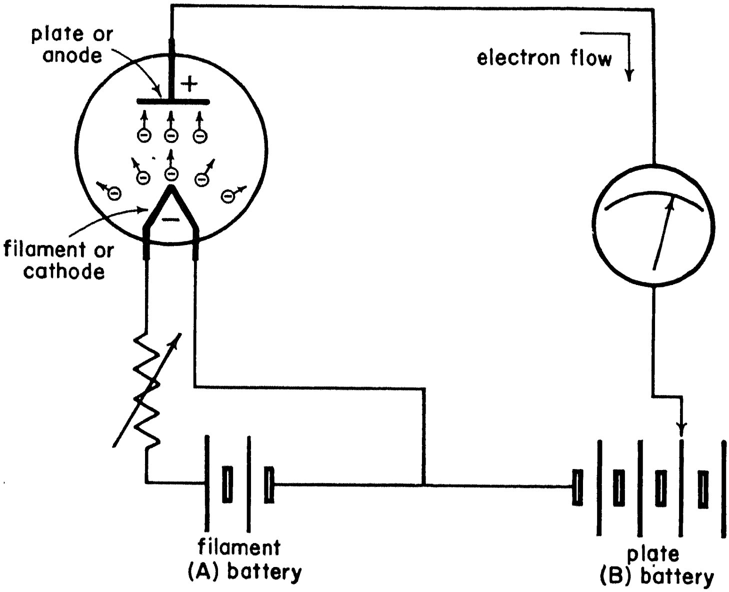


Fig. 390. Two-element vacuum tube, or diode. The "A" battery is solely to heat the filament. When the plate is made positive with respect to the filament or cathode by means of the "B" battery, electrons emitted by the hot filament or cathode are attracted to the positive plate or anode and flow back to the cathode as a current in the external circuit.

filament and a near-by plate, we heat the filament by setting up in it an electric current (steam heat would do just as well if the temperature were high enough), we find, as Edison did, that in a meter connected to the plate there is a current *only* when the plate is charged positively, that is, when the plate is made the anode and the filament the cathode (Fig. 390). The negative electrons from the filament are attracted to the plate when it is *positive* and are repelled when the plate is negative. Thus they flow from the filament to the plate, through the meter, and back to the filament only when the plate is positive.

If, when the plate is held positive, we raise the temperature of a cold tungsten filament by decreasing the resistance in the heating current circuit, we find that there is almost no electron emission at all until the tungsten begins to glow brightly. Then, when the

temperature is raised further, the emission increases very rapidly, as plotted in Fig. 391.

It is also interesting to see how the electron current to the plate depends on the voltage between the plate and filament. We

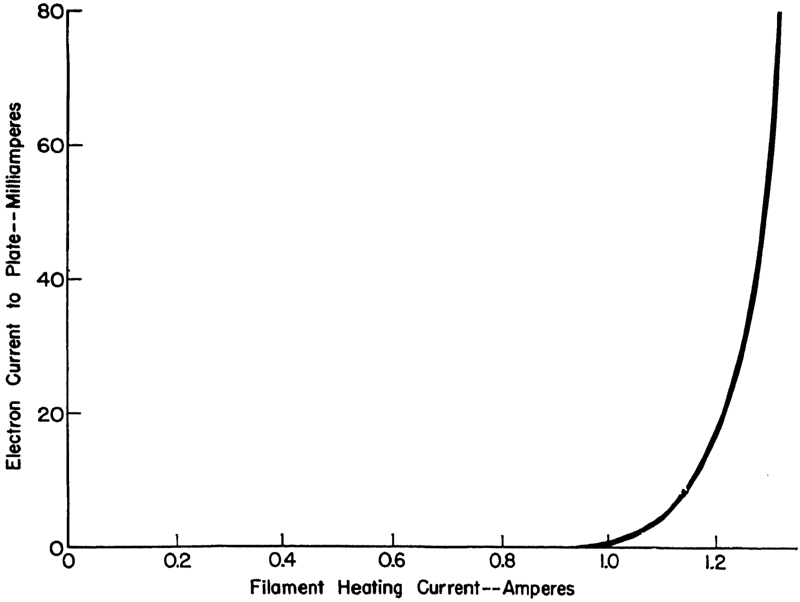


Fig. 391. Typical relation between current from cathode to plate (plate current) of a diode, and current heating the filament or cathode. The plate is maintained at a positive potential with respect to the cathode.

see (Fig. 392) that there is practically no electron current with zero "plate voltage" but that, as the voltage is increased, say by connecting into the circuit more and more cells of a battery, the electron current increases rapidly and then finally becomes practically constant. That it does not increase appreciably for higher voltages means that the electric field is already high enough to pull virtually all the emitted electrons to the plate; in other words, *saturation* has been reached.

The Diode a Rectifier. The new discovery was first put to work by Fleming in 1904. He saw that a two-element tube would make a splendid device to convert *alternating current* to *direct current,* that is, it would serve as a *rectifier.* Since electrons will flow from filament to plate when the plate is positive, but will not flow in the

reverse direction when the plate is negative, a diode is a "one-way street" for current. For example, if a diode with its plate and hot filament is connected in series with an AC source, say a transformer as in Fig. 393*a*, there is current in the resistance *R* only

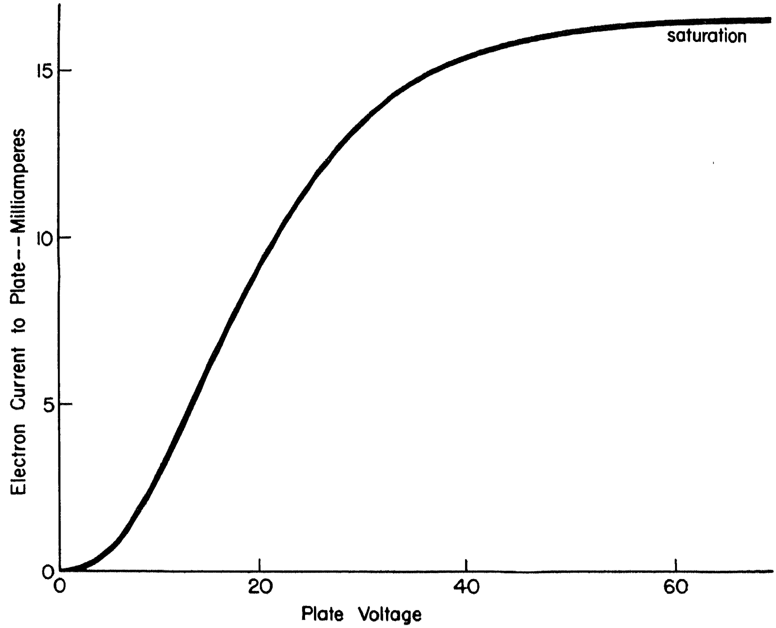


Fig. 392. Typical relation between plate current and plate voltage, i.e., voltage between plate and cathode, for a diode in which the filament heating current is constant. When the plate voltage is high enough to pull all the emitted electrons across to the plate, further increase in voltage cannot increase the plate current. Under this condition, the plate current is said to have reached its saturation value.

when the plate is positive. A cathode-ray oscillograph shows that current is in the circuit only during the positive half of the AC cycle (Fig. 393*b*). This so-called ***half-wave rectifier*** thus eliminates every other pulse of the alternating current, leaving current in one direction only. This resulting current might be pictured as "pulsating DC."

In order to provide more effective conversion, two diodes are often used to secure ***full-wave*** rectification. The transformer secondary is made in two parts, and, as can be seen in Fig. 394*a*, when one end of the transformer secondary is positive (during one half-cycle) only one rectifier is conducting, and when the other end is positive (on the next half-cycle) only the second

rectifier is conducting. The screen of the cathode-ray tube shows that there is current in the resistance on both halves of each cycle, that is, we have a *full wave rectifier* (Fig. 394*b*).

Filters. You might say that such "pulsating DC" is too

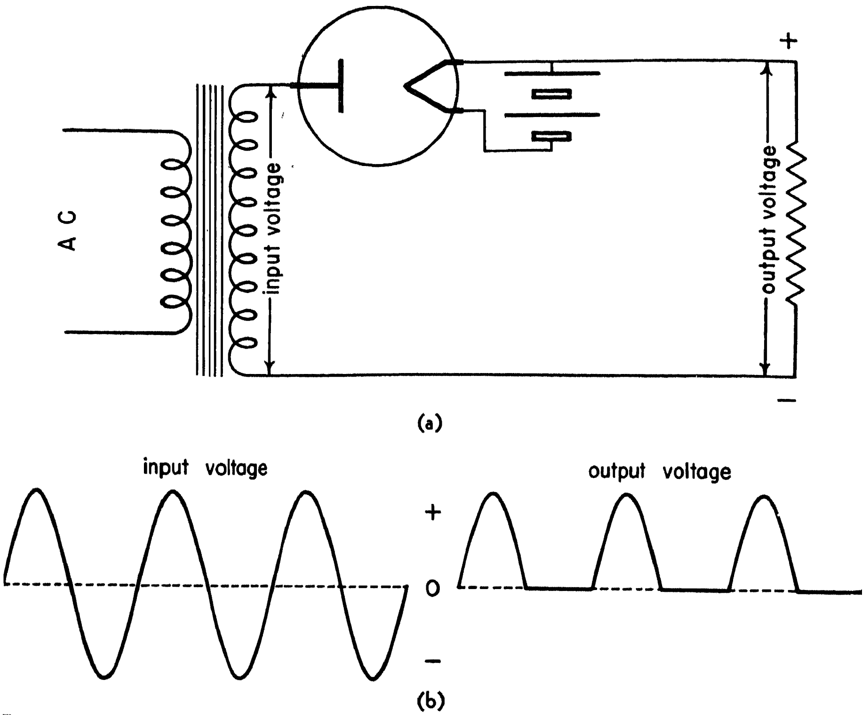


Fig. 393. (a) Diode as a half-wave rectifier. When AC voltage is applied between filament and plate, there is current through the tube only during the half-cycles in which the plate is positive (electrons from the cathode are repelled by a negative plate). (b) Input and output voltages of half-wave rectifier. There is current in the output resistance only when the plate of the diode is positive with respect to the cathode. Hence, by Ohm's law there is voltage across the resistance only during the alternate half-cycles in which that condition is satisfied.

unsteady to be very useful. Happily, though, it can be "smoothed out" by employing the ideas we learned about inductance and capacitance. The devices which accomplish this are called ***filters.*** An inductance has electrical inertia and tends to oppose changes in current. A condenser can store electric charge on one half of the cycle and discharge it on the other half. Thus, either alone would help to "smooth out" the current variations, but when we use them both, as in Fig. 395*a*, that is, an inductance in *series* with the rectifier and a capacitance in parallel, their combined effect

is to give to the current a steady value. A cathode-ray tube connected across the output resistance shows that the voltage, and thus the current, is indeed quite constant (Fig. 395*b*).

Rectifiers in Use. Rectifiers find all sorts of application today.

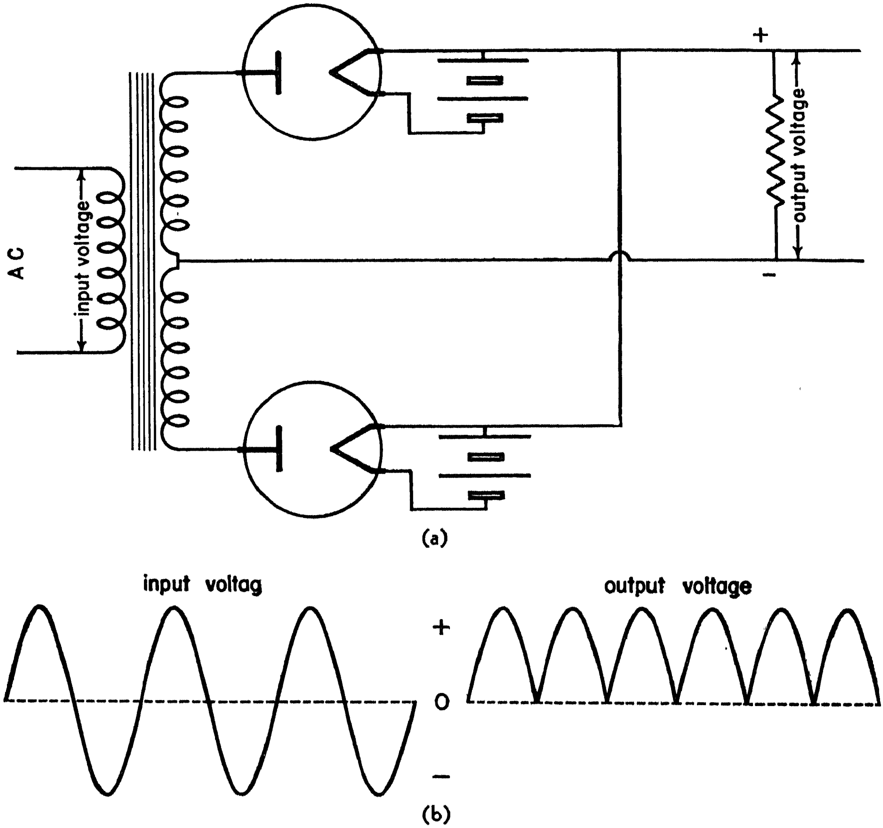


Fig. 394. (a) Two diodes connected as a full-wave rectifier. During one half-cycle the upper tube passes current through the output resistance and during the next half-cycle the other tube passes current through the resistance in the same direction. In practice the cathodes are usually heated by a low-voltage secondary winding on the same transformer, rather than by batteries. (b) Input and output voltage of full-wave rectifier. The effect is to change the sign of the negative half-cycles of the AC input.

Conveniently, a transformer may be employed either to ***step up*** or to ***step down*** the voltage before rectification. Your AC radio set uses a system similar to that in Fig. 395 to supply the DC voltage required for the plates of the vacuum tubes, but the voltage is usually first stepped up by a transformer so that some 300 volts steady DC may be produced from only 120 volts AC.

Radio transmitting stations often use large rectifier tubes and transformers to supply more than 10 amp at 20,000 volts. Nearly 3 million volts DC have been produced for large X-ray tubes and for "atom-smashing" work by use of very high voltage step-up

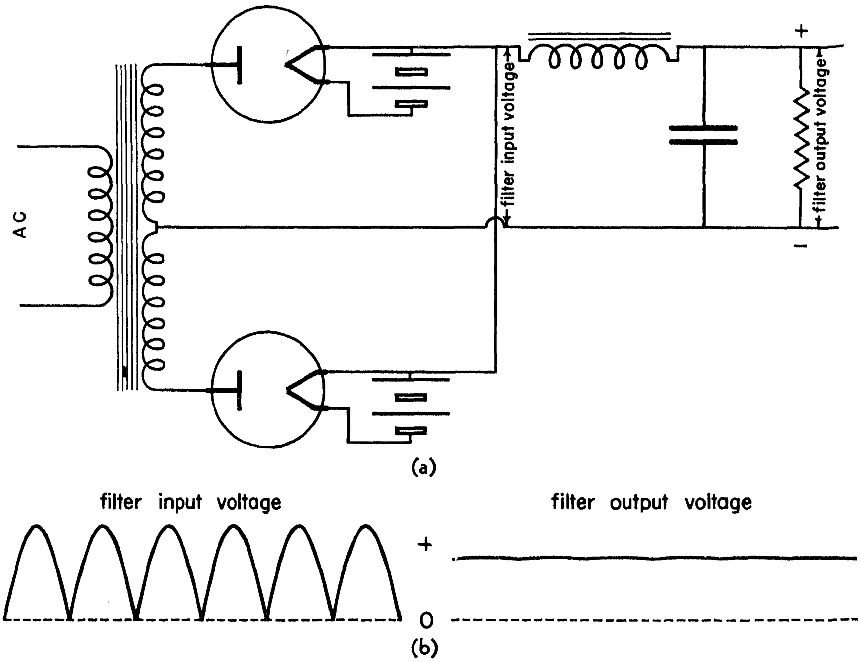


Fig. 395. (a) Full-wave rectifier with filter. An inductance in series and a capacitance in parallel with the output resistance "smooth out" the fluctuations in voltage from a rectifier. (b) Pulsating voltage supplied to the filter by the full-wave rectifier, and "smoothed DC" output voltage from the filter. The effectiveness of a filter may be increased by making it of several successive sections as the one in (a), each consisting of a series inductance and parallel capacitance. Note that the filtered DC voltage is less than the peaks of unfiltered "pulsating DC."

transformers and special rectifier tubes to withstand the high voltage. The ***detector*** in your radio set (see page 522) is ordinarily just a small diode used to convert very high frequency alternating current to "pulsating DC."

THE THREE-ELEMENT TUBE OR TRIODE

In 1907, Lee de Forest discovered how to make a vacuum tube amplify and thereby began one of the greatest of electron tube developments. He inserted an additional electrode close to the filament, between it and the plate. This electrode, called the ***grid,*** was a comparatively open wire screen. Since the grid is so close to

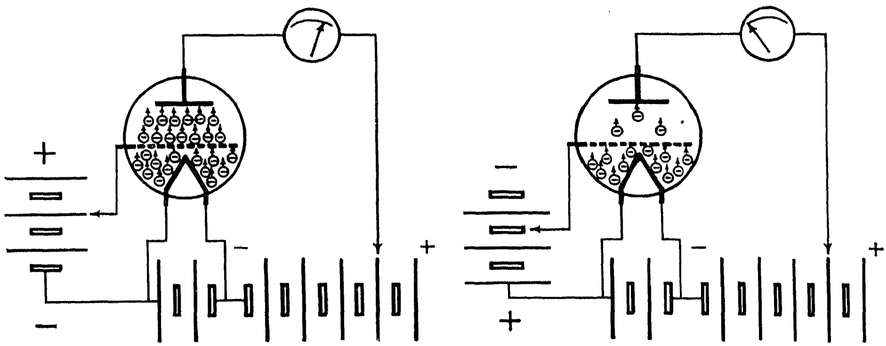


Fig. 396. Three-element vacuum tube, or triode. An open, wire grid interposed between cathode and plate exerts strong control over the electron flow.
When the grid is made positive with respect to the cathode, the electrons are attracted toward the plate and a large plate current results.
When the grid is at a negative potential, the electrons are repelled by it, and the plate current decreases. Since the grid is much closer to the cathode than the plate, the grid potential is much more effective than the plate potential in controlling the electron flow.

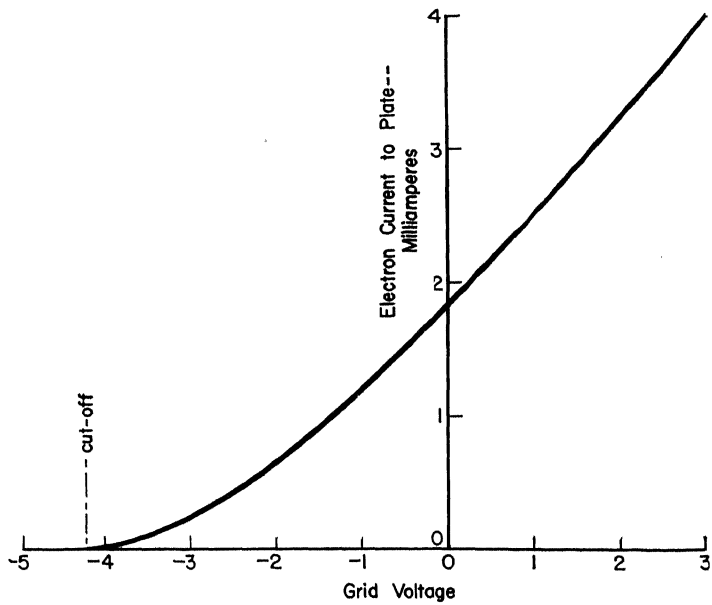


Fig. 397. Typical relation between plate current and grid voltage for a triode. A few volts (negative) on the grid (the "cutoff" voltage) is sufficient to stop the flow of electrons from filament to plate.

the filament, it is in the midst of the emitted electron cloud (Fig. 396) so that it exerts a much stronger controlling effect on the electron current to the plate than does the plate itself. Figure 397 gives an idea of the great effectiveness of this control.

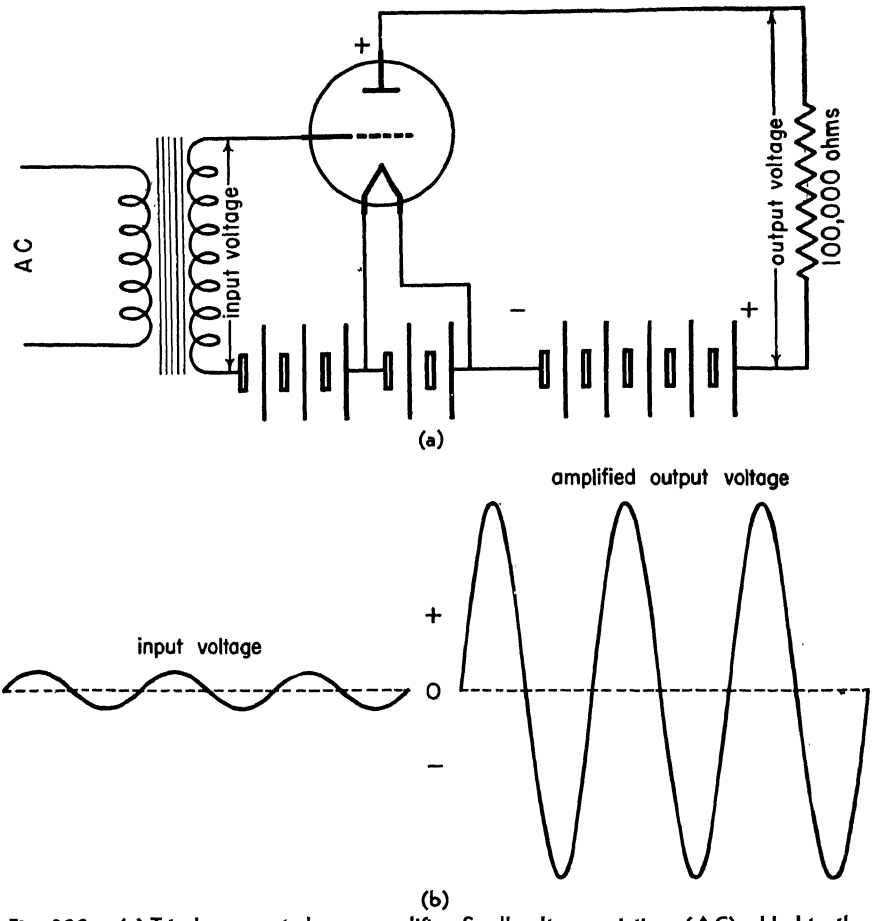
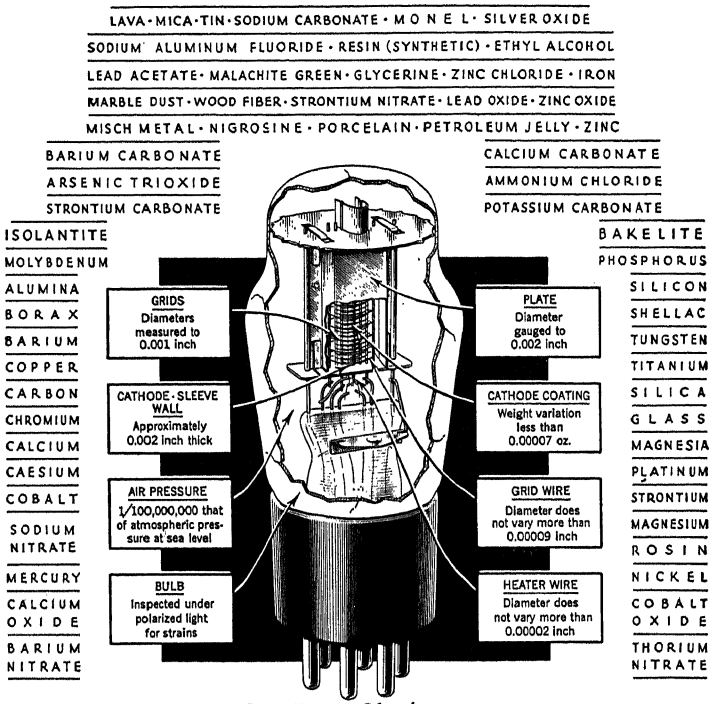


Fig. 398. (a) Triode connected as an amplifier. Small voltage variations (AC) added to the DC grid voltage produce relatively great changes in plate current, hence (by Ohm's law) large voltage variations across a high resistance in the plate circuit. (b) AC voltage applied to grid of amplifier tube (input voltage), and amplified AC voltage across a high resistance in the plate circuit (output voltage).

If the grid is first at the filament potential and then is made more negative in steps, it more effectively repels electrons on their way to the plate and therefore reduces the electron current. If made negative enough, the grid will almost completely stop the

electron flow, and in this condition the current is said to be "cut off." If the grid is then made positive, it attracts the electrons and greatly increases the electron current to the plate. Being comparatively open, the grid does not intercept many of the electrons. It



Gases Used in Manufacture

NEON — HYDROGEN — CARBON DIOXIDE — ILLUMINATING GAS
HELIUM — ARGON — NATURAL GAS — NITROGEN — OXYGEN

Elements Entering into the Manufacture

ARGON — ALUMINUM — BORON — BARIUM — CAESIUM — CALCIUM — COPPER — CARBON — CHROMIUM — CHLORINE
COBALT — HYDROGEN — HELIUM — IRIDIUM — IRON — LEAD — MAGNESIUM — MERCURY — MOLYBDENUM
NICKEL — NEON — NITROGEN — OXYGEN — POTASSIUM — PHOSPHORUS — PLATINUM — SODIUM — SILVER
SILICON — STRONTIUM — TUNGSTEN — THORIUM — TANTALUM — TITANIUM — TIN — ZINC — RARE EARTHS

(*Radio Corporation of America.*)

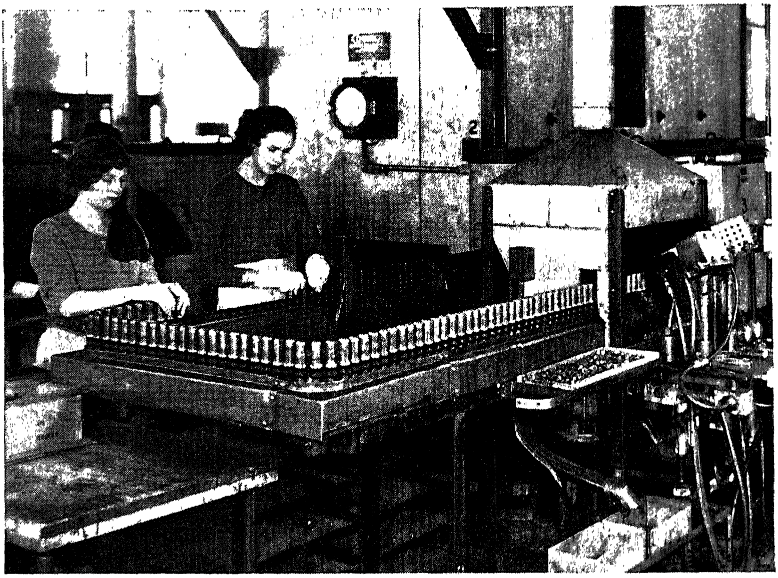
Fig. 399.

thus acts like a ***valve*** to ***control*** a large amount of electron flow but itself requires very little current to operate. In fact, ***valve*** is the name used in England for such a vacuum tube.

Suppose, for example, that the grid in Fig. 396 is at -3 volts;[1] then the plate current might be 3 milliamperes (0.003 amp). When the grid potential is changed to -2 volts, the plate current might

[1] Grid and plate potentials are always measured with respect to the filament, or cathode.

increase to 4 milliamp. In this case, a change of 1 volt on the grid would change the plate current 1 milliamp. If, however, the grid voltage is not varied, the ***plate potential*** has to be increased 20 volts to produce the same current change. The grid is thus twenty



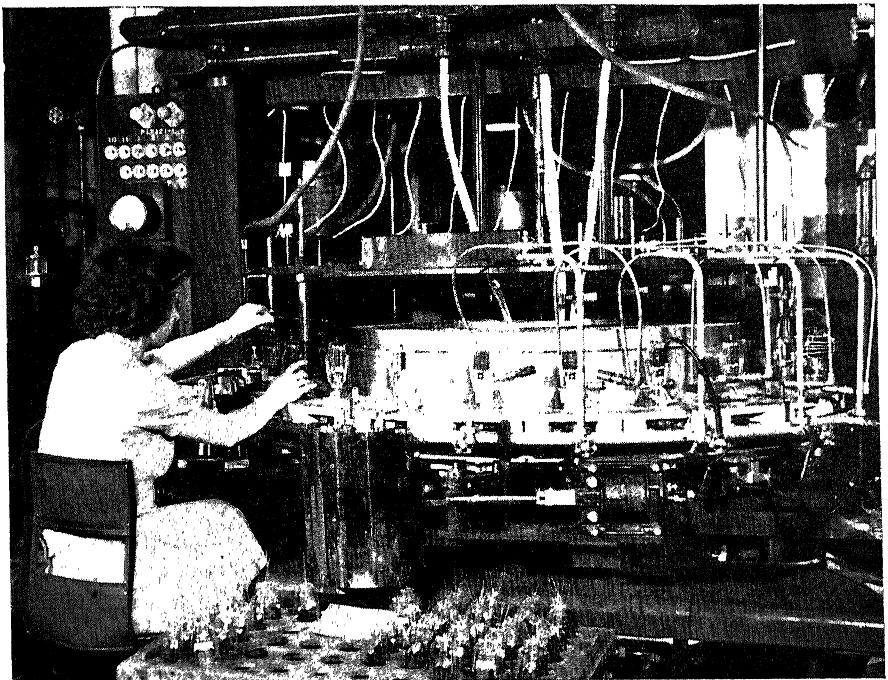
(Radio Corporation of America.)

Fig. 400. Quantity production of metal vacuum tubes. This machine spray-paints and bakes the shells of metal tubes at the rate of 7,200 an hour.

times more effective than the plate in controlling the electron current. This fact makes it possible to use the triode as an ***amplifier***. We say that this particular tube has an ***amplification factor*** of 20.

Amplifiers. One way in which a triode may be used as an amplifier is represented in Fig. 398*a*. If a small alternating voltage is applied in the grid, or input, circuit by means of a transformer, a cathode-ray oscillograph shows that the voltage across a high resistance placed in the plate, or output, circuit is like the input voltage in form but is many times greater in magnitude (Fig. 398*b*). The small changes of voltage on the grid are so effective in controlling the electron flow in the plate circuit that high amplification is secured.

Multielement Tubes. In recent years, research has shown that much higher amplification and certain other technical advantages may be obtained by adding a fourth, a fifth, or even more elec-



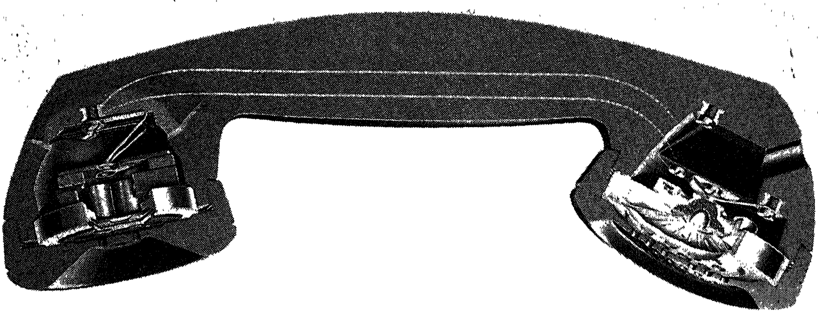
(*Westinghouse Electric and Manufacturing Company.*)

Fig. 401. Automatic machine for exhausting the air from small transmitter tubes. The intermittently moving rim of the machine revolves once in about 20 minutes. During that time a dozen different heating, baking, and pumping operations take place on the tubes that it carries.

trodes, in the form of additional grids between the cathode and plate. Amplification factors of more than 2,000 may be obtained with ***pentodes*** (five-element tubes), although the gain actually realized in a pentode in your radio set is seldom more than 150 to 200.

It is worth noting that the cathode in most modern tubes is not a single wire filament but a small tube of nickel coated with barium and strontium oxides and heated indirectly by an insulated filament inside. To make multielement tubes with complex cathodes by automatic machinery for only a few cents each is a great achievement of American mass production methods.

Many-stage Amplifiers. The ability to amplify small voltages is of vital importance in all fields of communication. If more amplification is desired than can be given by the single ***stage*** of Fig. 398*a*, the output of this one stage may be fed to a succeeding stage and amplified further in ***cascade*** fashion. In some cases even



(*Bell Telephone Laboratories.*)

Fig. 402. Telephone handset. In the carbon-granule microphone (right) sound-pressure variations acting upon the thin diaphragm vary the pressure on the carbon granules. This changes the effective resistance of the cup of carbon granules. Thus variations in the current through the carbon microphone, corresponding to the sound pressure variations, are sent through the telephone lines to operate a distant receiver.
The magnetic receiver (left) consists of an electromagnet acting upon a thin diaphragm of magnetic material. Electrical current variations which correspond to sound variations cause the electromagnet to exert varying forces on the diaphragm, vibrating the diaphragm and setting up sound waves in the air adjacent to it.

six to ten stages are used to produce amplifications up to 10^{10} times. There are, however, always small disturbances present in vacuum tubes and circuits. These prevent satisfactory amplification of voltages lower than about 1/10,000,000 volt. Even the "rustling" of the electrons themselves as they patter against the plate may be heard with such amplification.

When you make a long-distance telephone call to San Francisco, 2,500 miles from New York, you depend upon vacuum tube amplifiers. Without them, the feeble "voice currents" from your telephone transmitter would be so attenuated as to give quite unsatisfactory sound reproduction at distances of even less than a hundred miles. So these amplifiers, called ***repeaters,*** are inserted in the lines, usually every 25 miles, to send on with renewed vigor the currents representing your voice.

Physicists find vacuum tubes invaluable as tools to detect currents sometimes as low as a hundred electrons per second, or even to record the effects of single atoms!

Do we get something for nothing with electronic amplifiers? Of course the answer is no. The electric energy must be supplied by the battery or rectifier in the plate circuit and by the other sources

of potential, so one always really "loses" energy, as with any machine, regardless of mechanical advantage. However, the energy used in most amplifiers is small, and the results accomplished are more than worth the expenditure.

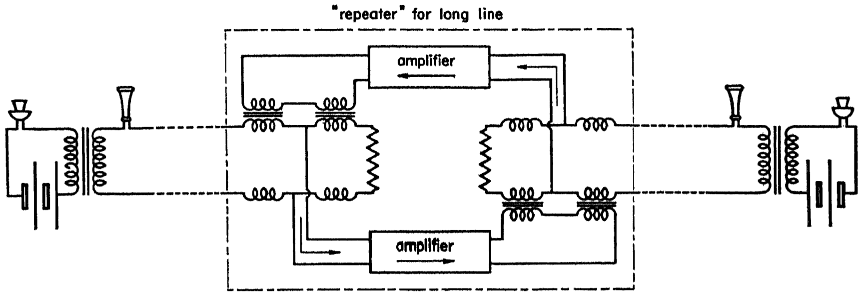


Fig. 403. Simplified telephone system with "repeater" inserted for long-distance transmission. Note that the two amplifiers of the repeater are connected so that the output of one cannot "feed" into the other. Thus, the upper amplifier acts only on signals going to the left and the lower one on signals to the right.

RADIO

Producing Continuous Waves. The old spark discharge oscillating circuits such as that shown in Fig. 387 were used widely for communication during a number of years. The damped oscillatory discharges, when led to long elevated wires, or antennas, produced

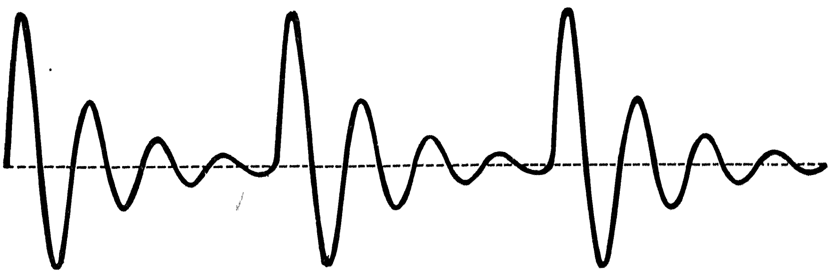


Fig. 404. Oscillograph record of the high-frequency AC in a circuit in which there is a series of damped oscillatory discharges.

high-frequency alternating currents which radiated waves that were effective over great distances. These currents could be "keyed" to produce long or short series of rough discharges which simulated the dots and dashes of code.

It is not difficult to see that steady "continuous" oscillations are much more desirable than these sputtering series of damped oscillations. One obvious method of obtaining "continuous waves"

is, in effect, to run an ordinary alternating-current generator at high speeds. Indeed, this was done with some success, although a mechanical device can hardly be run fast enough to produce frequencies as high as can be obtained from oscillating circuits.

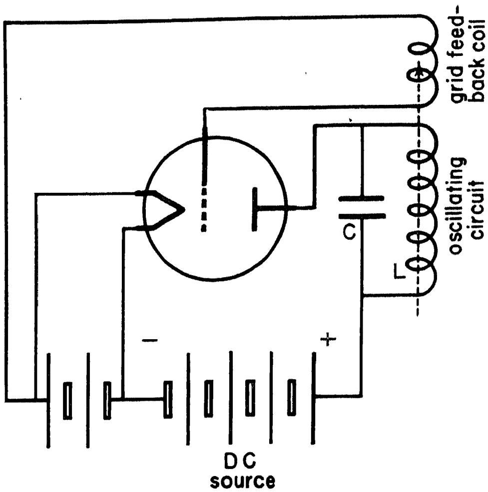


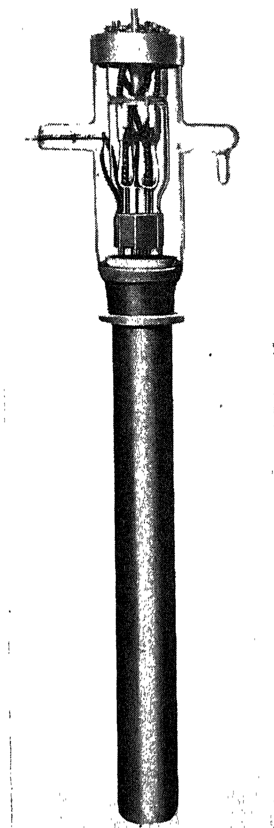
Fig. 405. Simple vacuum-tube oscillator. Current variations in the resonant "oscillating circuit" induce voltage variations in the adjacent feed-back coil in the grid circuit. These induced grid voltages are amplified and reinforce the oscillations in the resonant plate circuit. Thus a small amount of power fed back to the grid maintains steady oscillations in the plate circuit.

Vacuum Tube Oscillators. De Forest's invention of the three-element amplifying electron tube made possible a new development—production of continuous high-frequency alternating current by simple apparatus. E. H. Armstrong, then an undergraduate student at Columbia, was probably the first to see (in 1910) how a vacuum tube could be connected to an oscillating circuit so as to give the circuit correctly timed "kicks" which keep it in steady oscillation. The electron tube controls the oscillation much as a spring and escapement mechanism can be arranged to feed energy to a clock's pendulum and keep it swinging steadily.

The method by which a "vacuum tube oscillator" works is quite simple. Figure 405 shows one of the numerous ways of arranging such a device. The resonant or "oscillating circuit" with its inductance and capacitance is connected into the "plate circuit" of the tube. A small coil connected in the grid, or input, circuit is placed near this oscillating circuit. Now if small oscilla-

tions are started in the resonant circuit some of the energy is picked up by the grid coil and in this way is fed back to the grid circuit. As we learned, the small voltage changes thus introduced onto the grid are amplified, so that they cause larger oscillations in the plate circuit. The amplified oscillations again are "fed back" to the grid, once more amplified, and so on, to increase more and more. Thus a "regenerative" build-up action occurs, resulting in large oscillating currents that are limited only by the resistance of the circuits and the power which the vacuum tube can accommodate and which the power sources can supply.

It is apparent that the vacuum tube makes a very convenient device for feeding energy from a steady direct current source (mainly the plate voltage supply) to maintain oscillations in a typical circuit which has inductance and capacitance. The frequency, $f = 1/(2\pi\sqrt{LC})$, of the alternating currents generated by such a device depends only on the effective inductance L and capacitance C of the oscillating circuit, which often are arranged to be varied conveniently over wide limits. Frequencies ranging from nearly zero to between 10^9 and 10^{10} cycles per second have been produced by these methods. Huge vacuum tubes with water-cooled electrodes can be made to produce high-frequency power up to 1 million watts. As much as 200,000 watts of power can be radiated into space from the antennas of large broadcasting stations.

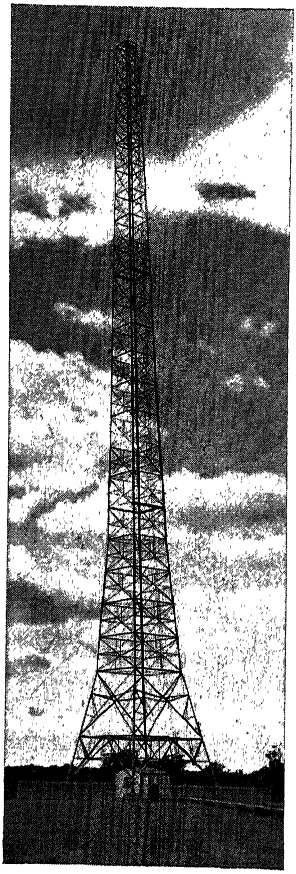


(Westinghouse Electric and Manufacturing Company.)

Fig. 406. One hundred-kilowatt transmitter tube. This water-cooled tube stands five feet in height.

Voice and Music Ride the Waves. About 1916, many investigators began to experiment with ways of transmitting voice over radio waves, and in 1920 the pioneer broadcasting station KDKA of the Westinghouse Company in Pittsburgh began sending out speech and music. Today radio broadcasting is a big business, and

many hundreds of stations literally "fill the air" with programs for good or for bad. Often a hundred stations may broadcast the same program, which is usually distributed to them over land telephone lines from studios in centers such as New York City. Furthermore, governments and political groups have discovered that news or propaganda may be directed to peoples all over the world.



(*National Broadcasting Company.*)
Fig. 407. Transmitting antenna of the "quarter-wave" type, i.e., height of antenna is equal to one quarter of the length of the radiated wave.

Our space is too limited to study the details of radio broadcasting and receiving processes, but we ought to understand the essential physical principles.

Amplitude Modulation. In order to superimpose messages on radio waves, a process of ***modulation*** is used. The main oscillating circuit produces alternating current of very high f r e q u e n c y, which ultimately controls currents in the transmitting antenna that radiate waves of a fixed frequency—between 1,500 and 550 kilocycles per second for ordinary broadcasting (wave lengths of 200 to 545 meters). Now normal sound frequencies range from about 40 to at least 5,000 cycles per second, and it is necessary that the higher frequency radio waves somehow "carry" these slower vibrations.

In the broadcasting studio, pressure variations in the sound waves are converted by a microphone into weak electric pulsations, the forms of which are exact replicas of the sound waves. These weak electrical variations are then amplified successively by larger and larger tubes. The powerful electrical variations thus produced still correspond to the original sound frequencies and may be used to ***control*** the ***amplitude*** of the high-frequency alternating current in the transmitting station's antenna (Fig. 408). This is usually accomplished by controlling, or

modulating, the currents in the large tubes which take part in producing the high-frequency alternations.

By this general method, the amplitude of the radio waves which are radiated into space is made to vary in exactly the same way as

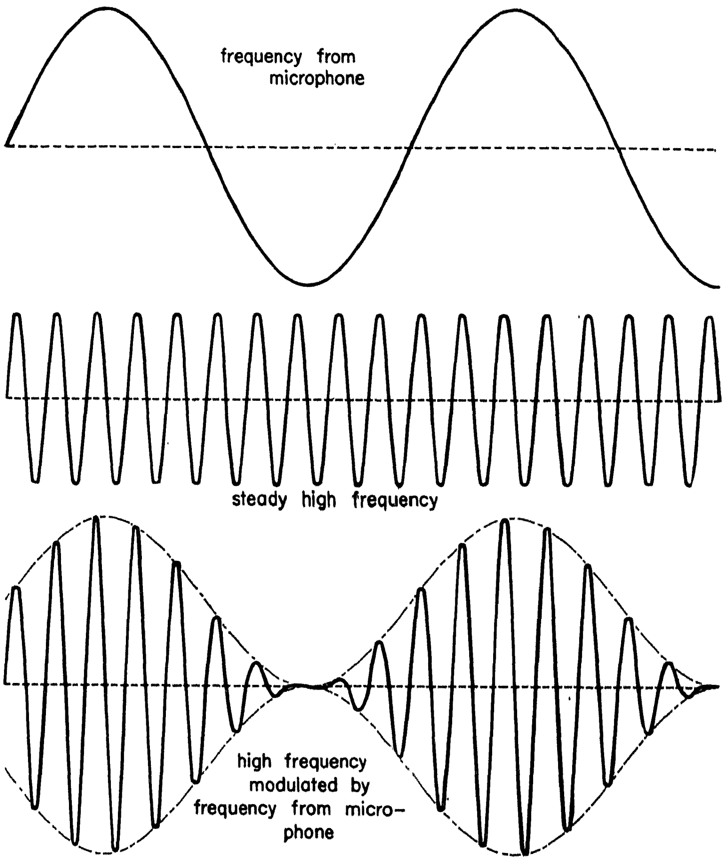
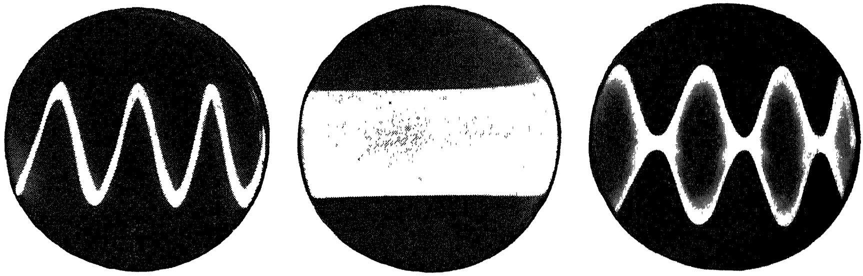


Fig. 408. Amplitude modulation. High frequency AC or radio frequency (assigned to the particular transmitting station) is made to vary so that its amplitude "follows" the electrical variations from the studio microphones which have comparatively low sound or audio frequencies.

the pressure variations in the sound waves entering the microphone. In other words, the high-frequency radio waves have been "modulated" so as to carry the "form" of the low-frequency sound vibrations. This method is usually called ***amplitude modulation*** (AM).

Frequency Modulation. Recently a method of modulation known as *frequency modulation* (FM) has been developed for



(a) (b) (c)

(*Radio Corporation of America.*)

Fig. 409. Oscillograph records illustrating amplitude modulation. (a) Voice (audio) frequency AC; (b) steady high-frequency AC of frequency assigned to radio station; and (c) high frequency modulated by the audio frequency. Note that the high-frequency variations in (b) are too rapid for the individual cycles to show up without "magnification" of the oscillograph time scale.

practical use, largely by E. H. Armstrong, now a professor in electrical engineering at the same university where as a student he had done pioneering work with vacuum tube oscillators. In frequency modulation the ***frequency*** of the high-frequency alternating current in the transmitting station antenna is caused to vary in exact accordance with the sound pressure variations, while the ***amplitude remains constant.*** For frequency modulation special receivers must be used, but it can have the great advantage of almost eliminating "static" crashes and man-made electrical interference which so often proves annoying in the conventional amplitude modulation system. Even near-by lightning flashes which may carry 250,000 amperes to earth are hardly noticeable with the better frequency modulation receivers.

In either type of modulation, AM or FM, the essential thing is that the high-frequency radio waves are made to vary, either in amplitude or in frequency, with the pattern of the low-frequency sound waves. Thus speech or music is literally made to ride the waves.

Receiving Radio Waves. The modulated waves radiated from a sending station's antenna usually travel outward in all directions, spreading, and diminishing in intensity. On the other hand, in some cases, particularly with very short wave lengths, it has been found possible to focus the waves into a beam in one direction by use of reflector systems. Reflections from the ionized layer above the earth aid the waves of ordinary broadcast lengths to travel

around the curved surface of the earth. However, for the very short waves less than ten meters in length, such as are used for television or frequency modulation, little reflection occurs, and signals usually cannot be picked up far beyond the region where

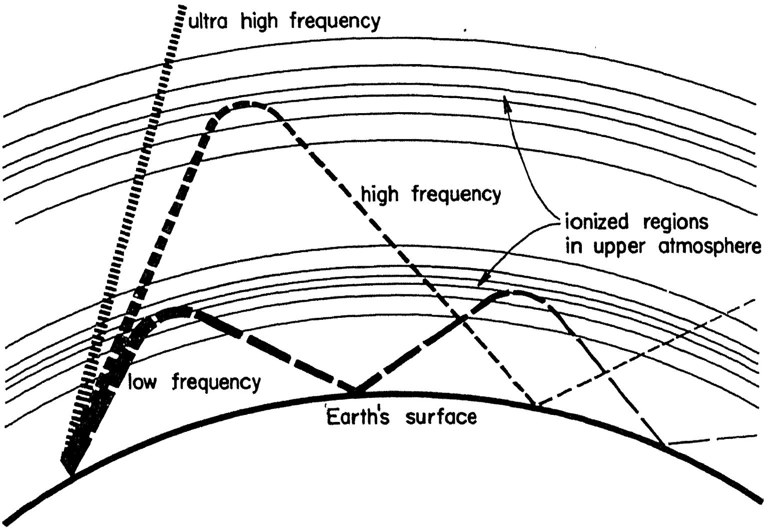
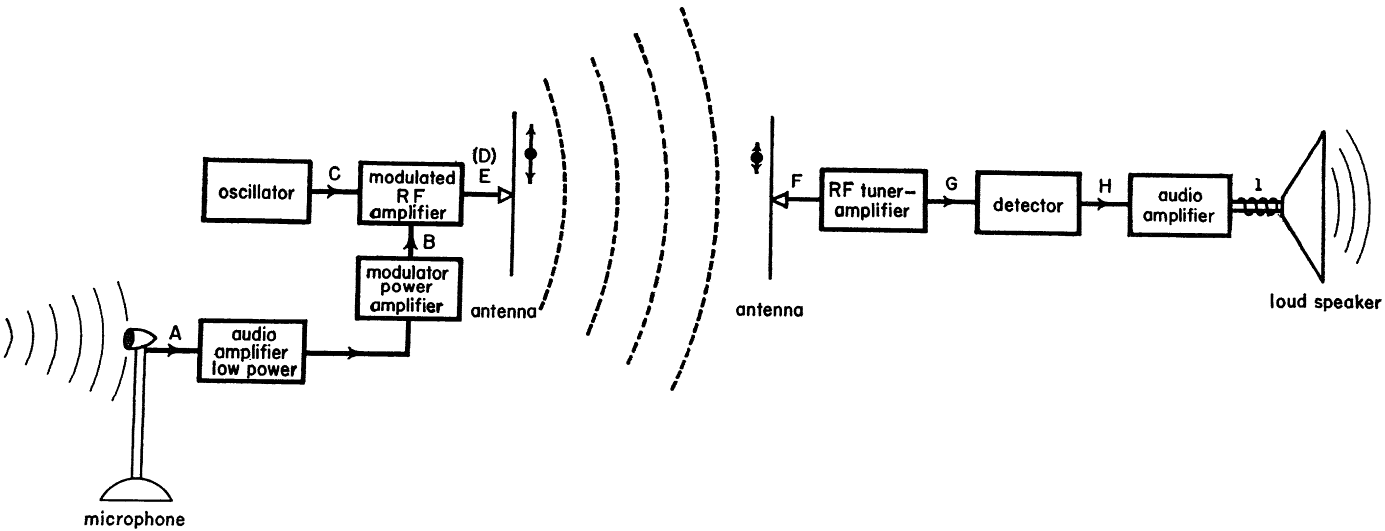


Fig. 410. Radio waves of various frequency ranges are affected differently by the ionized regions in the upper atmosphere. (See pages 400, 481.) Low-frequency (long-wave) signals are reflected back and forth between the lowest ionized region (Kennelly-Heaviside layer) and the earth's surface, so that they bounce around the earth, confined to the space between these two "shells."
Moderately high frequency waves penetrate the lower ionized region but are "reflected" by the upper regions. Accordingly, they return to earth at a greater distance from the transmitter than the low frequencies do, i.e., the "skip distance" is greater for the high frequencies. Ultrahigh-frequency (microwave) signals penetrate the ionized "layers" without reflection. Since the reflected wave is missing, the transmission range of these waves is limited practically to points from which the transmitter can be seen.

the sending station's antenna can just be seen. In spite of this limitation, short-wave signals from transmitters on a high point, such as the 1,250-ft Empire State Building, can be picked up easily at least 40, and sometimes as far as 100, miles away.

A varying radio wave, like any other electromagnetic radiation, consists of alternating electric and magnetic fields. Consequently, when passing over a receiving antenna wire, it induces small voltages in the wire, causing electrons to surge up and down in synchronism with the wave. It then remains for the *receiver* to translate these induced electrical variations into sound.



TRANSMITTER

Fig. 411a. Schematic diagram of radio transmitter and receiver. Weak audio frequencies from the microphone (A) are amplified first by an audio amplifier and then by a powerful modulator tube (B). High-frequency AC is generated by a small oscillator (C), and then is greatly amplified (D). The high-frequency amplifier is "controlled" by the modulator so that the high-frequency AC sent to the antenna is modulated (E), i.e., the high-frequency waves radiated into space are varied in amplitude to correspond to the audio frequencies from the microphone. Radio waves passing over the receiving antenna induce voltage variations in it (F). The tuner-amplifier may be set to select the particular frequency radiated by the desired station, and it amplifies the weak incoming modulated signal (G). The detector discards the high frequency and leaves the audio frequency that modulated it (H). This audio frequency is then amplified (I) and produces sound in a loud speaker.

While there are too many possible modifications and refinements of radio receiving circuits to discuss here, all receivers make use of the following essential principles:

1. All receivers have selecting systems, normally composed of

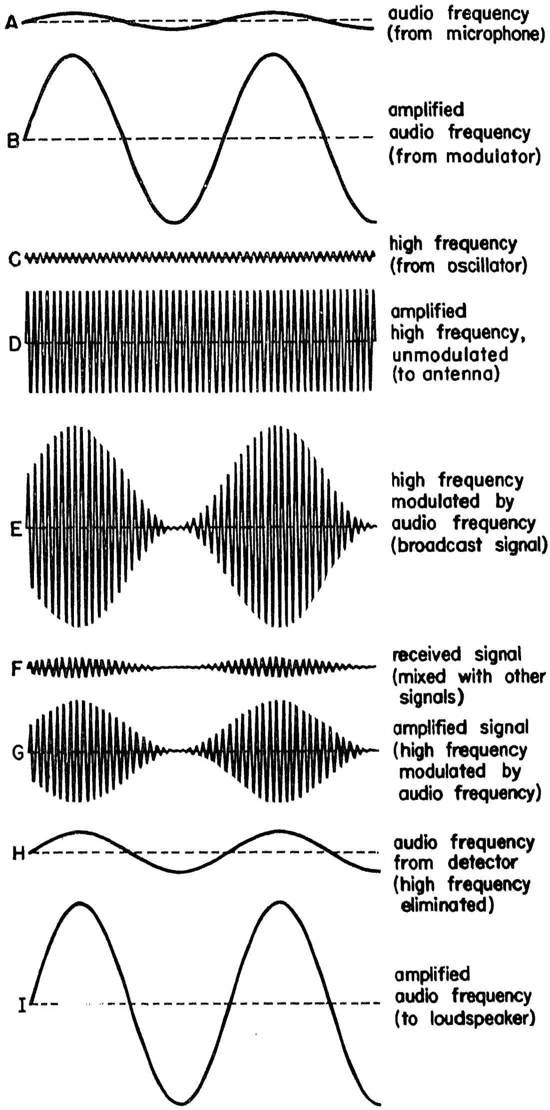
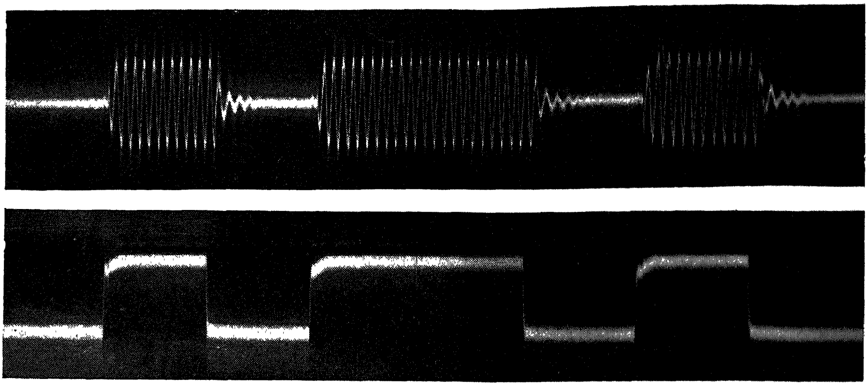


Fig. 411b. Oscillograph records of voltage variations at A, B, C, etc., in Fig. 411a.

fixed inductance coils and variable condensers, which can be tuned to resonate to the frequency of incoming feeble high-frequency



(*Bell Telephone Laboratories.*)

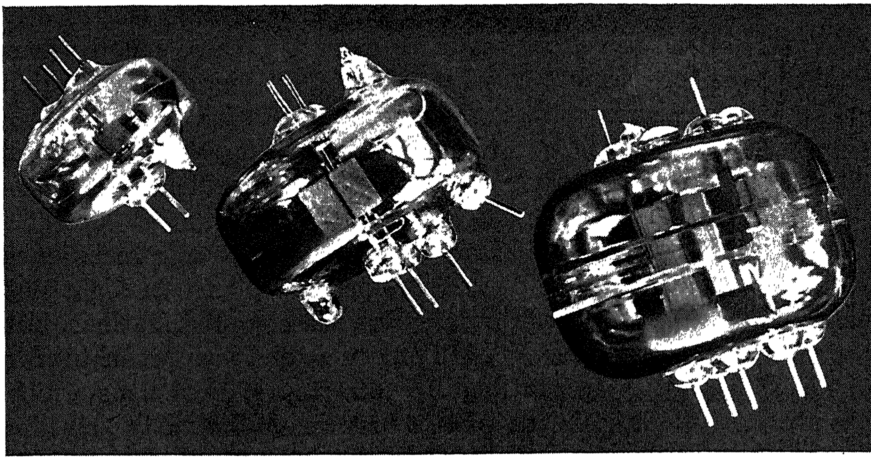
Fig. 412. Oscillograph records showing incoming radio-telegraph signal (top), and the signal after passage through the detector. This illustrates the action of the detector-rectifier which discards the high-frequency but leaves the low-frequency modulation.

currents induced in the antenna. The tuning is usually accomplished by rotating a dial on the variable condensers. Thus the receiver selectively responds to the frequency of the station to which it is tuned. Most receivers have several tuning circuits to increase the "selectivity."

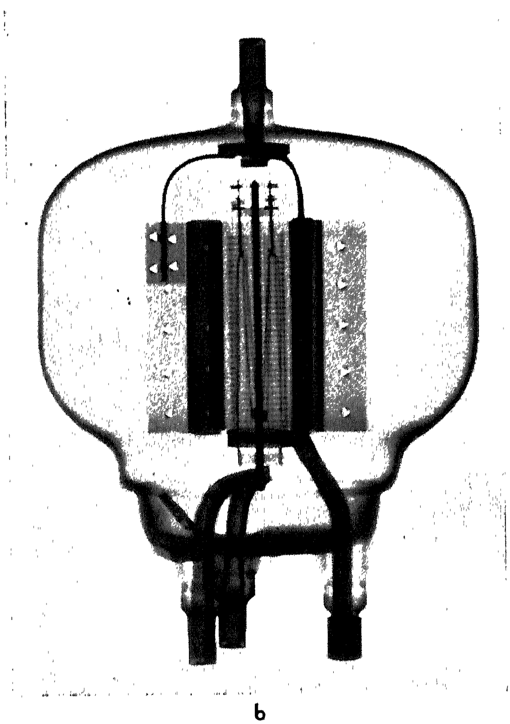
2. The feeble voltages at this high radio frequency are then amplified by vacuum tubes in what is often called the ***radio-frequency*** amplifier. Sometimes, as in the widely used "superheterodyne" receivers, the incoming signals are first combined with the frequency generated by a small oscillator in the receiver itself. The resulting "beat," or "heterodyne" frequency, which is the difference between the frequency received and the frequency of the local oscillator, is then amplified.

3. Next, the low frequencies which correspond to the desired sound vibrations are separated from the high frequencies on which they have been superimposed. This is done by means of a ***detector*** which is simply a ***rectifier*** that allows currents to pass only in one direction, with the result that it transmits pulsating low-frequency currents corresponding in frequency to the initial sound waves.

4. Finally, these low "audible frequency" pulsations are amplified in an ***audio amplifier.*** The currents are then large enough to cause appreciable forces to be exerted on some wires which are placed in a magnetic field within the loud speaker. In the end, the force on these wires causes the loud-speaker diaphragm to move back and forth, pushing and pulling on the air and thus producing



a



b

(*Bell Telephone Laboratories.*)

Fig. 413. (a) Vacuum tubes for ultrahigh frequencies. Note the short connecting wires and the small elements. (Slightly less than natural size.) (b) X-ray photograph of triode for use at high frequencies.

sound waves. If all of the complicated apparatus is properly designed and all the processes work correctly, these sound waves should reproduce almost exactly the original sound waves which entered the microphone at the transmitting station.

This description is of course very brief. If your curiosity is stimulated you can learn much more from the fuller discussions in the books mentioned at the end of this chapter.

Applications of Radio. Many applications of radio techniques have been and still are being developed. Airplanes in flight not only maintain two-way communication with ground stations, but they can fly entirely "blind" both on course and in approaching for landings. This is accomplished by directed radio beams which operate instruments on the pilot's instrument board to tell him just where he is and what he should do. Also, if ultrashort radio waves directed toward the earth from a plane can be reflected back, their time lag will measure the altitude accurately without the uncertainties of the old barometric-type altimeter.

Reflection of such directed radio beams from surfaces of moving planes opens the possibility of detecting and following planes at night as well as by day, a problem of utmost military importance.

The Klystron. In order to form powerful, narrow, well-focused radio beams for applications of the type just mentioned, it is essential to have ultrahigh-frequency waves. When the wave length is perhaps 10 cm or less (frequencies of 3×10^9/sec or greater) small reflectors can be used effectively to direct and focus the radiation. Ordinary types of radio tubes do not operate very successfully at these extremely short wave lengths, for the tubes must be made tiny so that the available power becomes exceedingly small. Furthermore an ordinary vacuum tube cannot operate well at a frequency so high that an electron starting from rest at the filament does not have enough time to reach the plate before the electric field reverses.

The recent development of the Klystron removes some of these fundamental limitations and permits relatively large amounts of power to be generated at very high frequencies. There are many possible forms of such devices, but in general all utilize two essential ideas: (1) Electric oscillations can take place inside hollow cavities by the surging of electron currents back and forth on the inner surface of the cavity. The wave length of these oscillations is about the average dimension of the cavity. (2) Such oscillations are set

up in the cavity by sending through it a focused beam of high-speed electrons which are "bunched" together in groups. These electron clusters have just the right speed and grouping to give successive "kicks" properly timed to maintain oscillations within the cavity

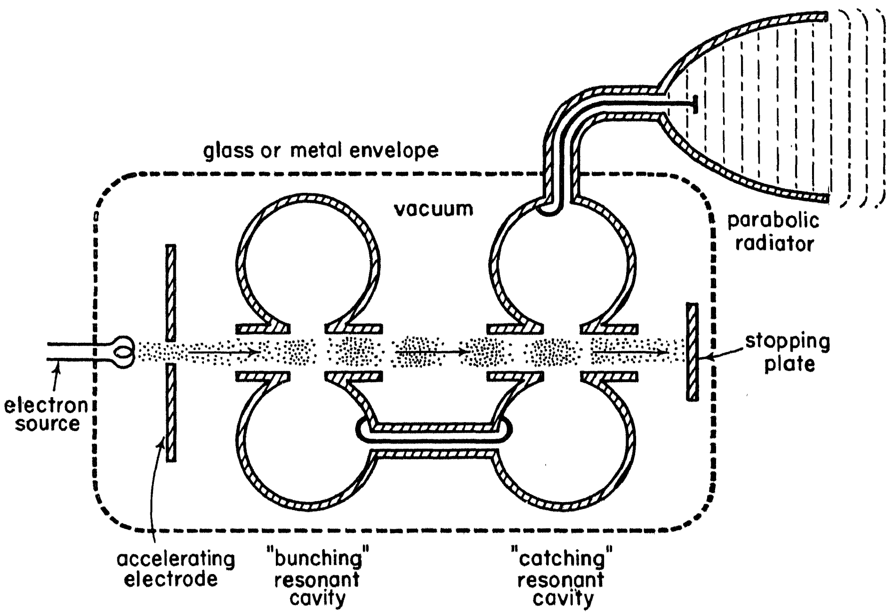


Fig. 414. Klystron, a vacuum tube for extremely high frequency. The electron current through the tube is made to alternate very rapidly by "bunching" the electrons in a continually moving beam rather than by starting and stopping the electron flow as in an ordinary oscillating vacuum tube.
The electrical resonant circuits are simply the two doughnut-shaped cavities within which electrical oscillations take place. These correspond roughly to grid and plate circuits of the ordinary vacuum tube oscillator, feed-back being accomplished by the conductor connecting the two cavities.
The antenna and parabolic reflector from which the electrical oscillations radiate very high frequency waves should actually appear much larger than the vacuum tube itself.

resonator. The "bunching" of the electrons may be accomplished by an electrode connected to the resonator and spaced just far enough from it so that the alternating voltage on the electrode alternately speeds up and retards the electrons in the beam. Thus the progressing electrons find themselves grouped in a series of "traffic jams."

The powerful high-frequency oscillations developed in devices such as the Klystron may be radiated by a small antenna placed

at the focus of a parabolic metal "mirror," to form intense parallel beams of radiation. These beams, which penetrate fog and clouds as well as darkness, present the intriguing possibility of "spot-lighting" objects which are undetectable by ordinary light beams.

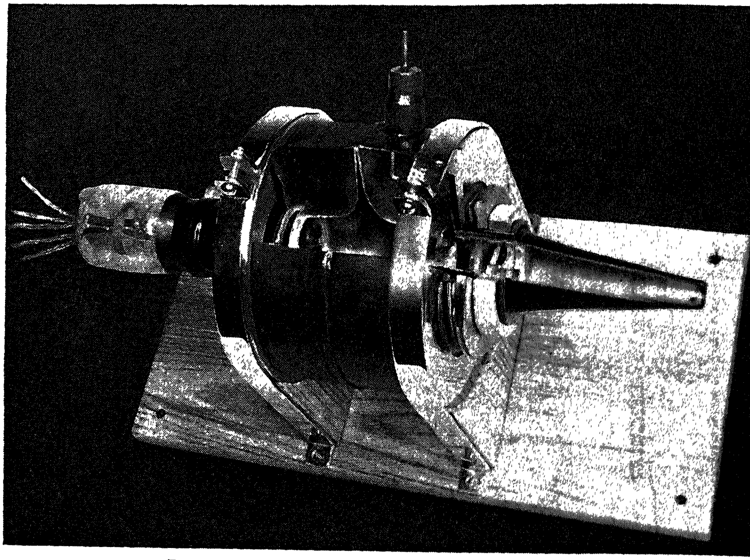


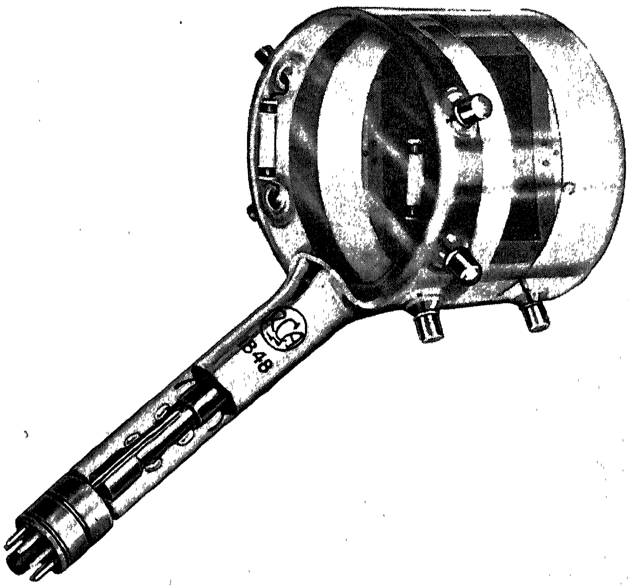
Fig. 415. Cutaway model of early Klystron.

TELEVISION

The transmission of images, as well as sound, over wires and through the air has long been a fascinating dream. Schemes for accomplishing this were talked of as long ago as 1884 when Nipkow first proposed the fundamental principle of television—that is, *scanning*. The realization of television had to wait many years, until the perfection of electronic devices.

Essentially, the basic principle of television scanning is to break the picture to be transmitted into small areas and transmit a separate signal for each small area. In effect, this is usually done by passing a small square opening along successive horizontal lines over the entire area of the picture. In this way, the picture is divided into a definite number of horizontal strips, and these strips are scanned in orderly succession from top to bottom. Light from the part of the picture seen through the opening is then impressed on a photoelectric cell which generates an electric current proportional to the brightness of that particular area. These varying

currents may be amplified and transmitted by wire or radio. Thus, as the picture is "scanned," electric current pulses are sent out, and the magnitude of each of these pulses is proportional to the brightness of the picture element being viewed at that moment.



(Radio Corporation of America.)

Fig. 416. Iconoscope.

At the receiver there can be a similar aperture that moves in exact synchronism with the one at the transmitter. The signal received is made to cause the light intensity on a screen to vary at each instant in exact accordance with the intensity of the picture element being viewed at the transmitter, and so a picture is built up which corresponds to the original.

A satisfactory television system must satisfy the following conditions: (1) The size of the elementary scanning area must be very small as compared with the whole picture, to provide "high definition" so that fine details can be seen. (2) The picture must be completely scanned at least sixteen times per second or it will seem to "flicker" badly. (3) The received picture should be bright enough and large enough to be seen easily.

Electronic Television. Early television systems used holes in rotating disks for apertures to accomplish the fundamental scanning and reconstruction operations which we have discussed. These methods, however, were not very satisfactory.

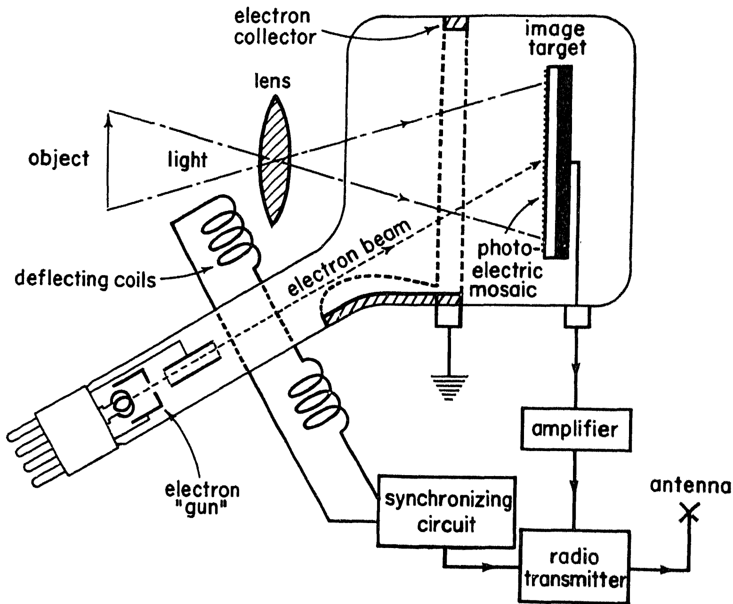
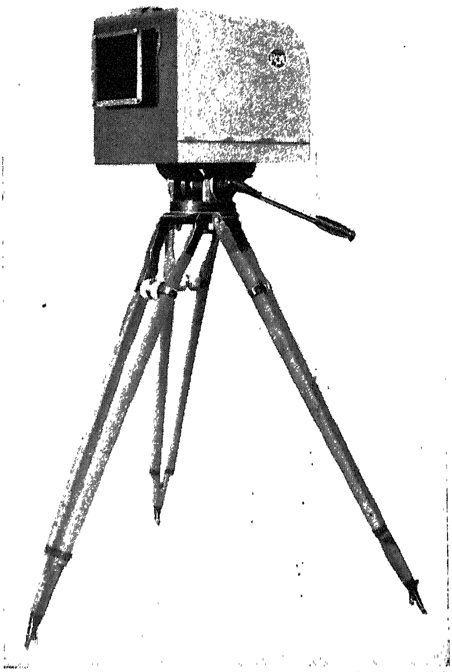


Fig. 417. Iconoscope or television transmission tube. Essentially a cathode-ray tube with a photoelectric mosaic in place of the screen. A light image focused on photomosaic is translated into electrical pulses as the electron scanning beam discharges the photoelectric globules. These pulses are amplified and broadcast along with a synchronizing signal. (For simplicity only one set of deflection coils is shown instead of two pair acting at right angles to each other.)

Remarkably high quality television systems have been achieved during the last few years. These were made possible through developments, particularly by Dr. V. K. Zworykin and P. Farnsworth, of electron beam devices and cathode-ray tubes to perform the essential television operations.

Iconoscope. The *iconoscope electronic image scanner* is now used widely for translating images into electric current variations. The picture to be transmitted first is focused by ordinary lenses on a mica screen covered with a vast number of insulated globules of photoelectrically sensitive material, a so-called "mosaic." The photoelectrons released from these globules leave behind positive

electric charges that are proportional to the intensity of the light falling on the photoelectric material. Next, an electron beam is caused to scan the entire image by sweeping back and forth across the mosaic screen in successive horizontal lines. This electron

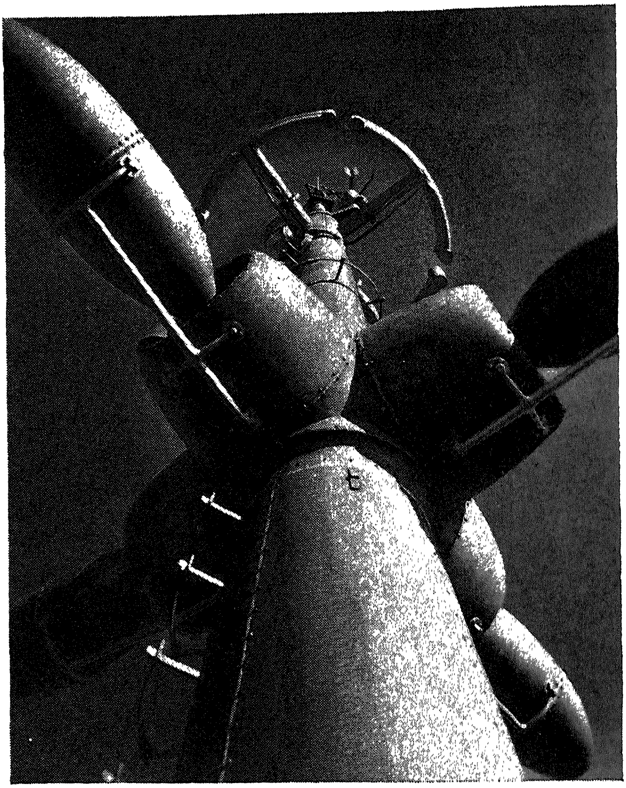


(*Radio Corporation of America-Victor Photograph.*)

Fig. 418. Television camera. Operator uses handle to focus camera, the iconoscope tube within transforming the scene before it into electrical impulses for telecasting.

beam, as it passes over the small areas, discharges each globule in turn; that is, it neutralizes the positive charges accumulated on the globules. Successive electric pulses corresponding to the brightness of the various parts of the image are thus "picked up" by the insulated metal plate just back of the globules. These pulses, often called "video" signals, are then transmitted by wire or radio.

At present, in order to secure reasonably good picture definition, the image is usually scanned in 441 separate lines. This corresponds in effect to 441^2 or 195,000 picture elements, and since the scanning operation is repeated thirty times per second to avoid flicker, this means that about 5,800,000 electric pulses must be transmitted each second! In transmitting sound, only frequencies



(National Broadcasting Company.)

Fig. 419. Television transmitting antenna on top of the Empire State Building.

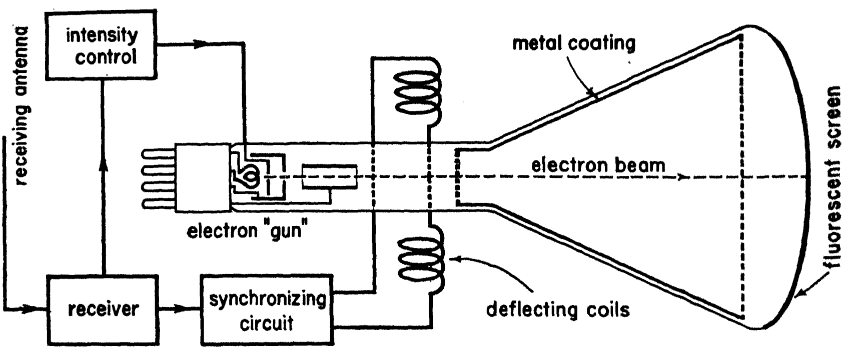


Fig. 420. Kinescope or television receiver tube. A cathode-ray tube in which the received picture signal varies the intensity of the electron beam while the synchronizing signal causes the beam to sweep rapidly across the fluorescent screen in successive lines. The result is that the televised pictures are traced on the screen many times each second. To avoid complication only one pair of deflecting coils is shown.

up to about 5,000 to 10,000 electrical vibrations per second need be transmitted, so the problem of television transmission is far more demanding in this respect.

Television Reception. In the modern television receiver, the modulated signals are received much as in conventional radio receivers. However, very high frequencies, corresponding to 6 to 8 meters wave length, are usually employed for the transmission.

The ***kinescope,*** largely used for reconstructing the received picture, is essentially a cathode-ray tube with a large fluorescent screen, often 12 in. in diameter and sometimes larger. The electron beam is caused to move horizontally across the screen in successive lines so as to cover the picture area. Exact synchronism with the iconoscope electron scanning beam is accomplished by a special synchronizing signal sent out from the transmitter. This "timing" signal controls the position of the spot which the receiving electron beam makes on the screen of the kinescope, while the intensity of the spot is controlled simultaneously by the received "video" signal. In this way, the rapidly moving electron beam "paints" the transmitted picture on the receiving screen.

(*Radio Corporation of America.*)

Fig. 421.—Twelve-inch Kinescope with "black and white" screen.

And so sight at last has conquered space. The pictures transmitted by radio are surprisingly good, and some special television screens can withstand such intensity that images from them may be projected optically onto large screens to be viewed by a considerable audience. Rapid improvements in definition and intensity of the images are being made, and even color television has been accomplished. However, serious problems yet remain to be solved, some economic, some technical. Among these is that of nation-wide

(*Bell Telephone Laboratories.*)

Fig. 422. Effect of increasing the number of scanning lines on picture transmission. The definition of the transmitted picture improves markedly with the increased number of scanning lines (left to right).

distribution. Ordinary telephone lines are not effective in transmitting the wide range of frequencies in the television signals, so very complicated and expensive methods must be resorted to.

The achievements of science in communication, used properly, can greatly enrich life. They provide the means of bringing the whole world together harmoniously, but that this is not the only choice has been demonstrated amply by the part which radio has played in the second World War to be witnessed by twentieth-century civilization.

FOR STUDY AND READING

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SUMMARY

The ***thermionic effect*** is the "evaporation" of electrons from materials at high temperature. Good electron emitters are tungsten and, at lower temperatures, thorium added to tungsten, or strontium and barium oxides on nickel.

In the two-element vacuum tube, or ***diode,*** electrons flow from the hot filament to the plate when the latter is positive, but not at all when it is negative. Electron emission begins at a high filament temperature and increases rapidly with further temperature rise. As the plate voltage is made more and more positive, the current first increases rapidly from zero, and then stops rising when

the voltage is high enough to pull all the electrons across to the plate.

An AC voltage across a diode produces "pulsating DC," that is, the alternating current is ***rectified.*** A ***filter,*** consisting of a condenser in parallel with the rectifier output and an inductance in series, smooths out the pulsating DC to give steady direct current.

The three-element vacuum tube, or ***triode,*** can be used as an ***amplifier,*** that is, an AC voltage between the ***grid*** and filament can produce a ***greater*** AC voltage on a resistance in the plate-filament circuit. Amplification can be increased by using several such "stages" or by employing "multielement" tubes.

Continuous electric oscillations, desirable for radio transmission, can be produced by a triode with a tuned plate circuit and an arrangement for feeding back to the grid a small part of the power from this circuit. Voltage fed from the plate circuit back to the grid reappears amplified in the plate circuit, thus increasing the feed back, etc. This produces steady oscillations timed to the natural frequency of the plate circuit. Their power comes chiefly from the DC plate voltage supply.

Sound broadcasting requires ***modulation*** or the impressing of sound frequencies on the higher frequency radio waves as variations either of the amplitude or the frequency of these waves.

In a receiver, high-frequency currents induced in the antenna by radio waves are selected by adjustable circuits ***tuned*** to their frequency. These currents are amplified and passed through a ***detector*** which suppresses all but the "carried" audible frequency pulsations. The latter are amplified and make a loud speaker produce sound waves.

The Klystron generates powerful ultrahigh-frequency waves which may be accurately focused, and has many interesting applications particularly for airplanes.

In television transmission, the picture is ***scanned,*** usually by an *Iconoscope* which combines the action of photoelectric cellules and an electron beam. This produces electric pulses proportional to the brightness of successive tiny areas of the picture. A timing signal is transmitted along with these pulses.

At the receiver, the picture is reconstructed by a cathode-ray tube. The deflection of the electron beam is controlled by the timing signal, and the intensity of the spot on the fluorescent screen by the received electric pulses.

QUESTIONS

1. What was the "Edison effect"? How was it related to *thermionic emission?*
2. How are electrons liberated from hot metal surfaces?
3. Why are such elements as tungsten or platinum used for electron-emitting filaments?
4. Why are oxide-coated filaments so widely used as electron emitters?
5. Why have improvements in high vacuum techniques played such an important role in thermionic developments?
6. How does the number of electrons emitted per second by a filament depend upon the temperature?
7. What is the meaning of the *saturation current* of a vacuum tube?
8. How are *diodes* used as rectifiers?
9. What are electric *filters* and how are they used?
10. How is amplification made possible by the insertion of a grid in a vacuum tube?
11. How may amplification be increased above that obtainable with a single triode circuit?
12. If a six-stage amplifier gives an over-all amplification of 10^6, what is the average amplification per stage?
13. What advantage have continuous oscillations over the old damped oscillatory spark discharges for wireless transmission?
14. How does a simple vacuum tube *oscillator* function?
15. What two types of modulation are commonly employed in radio transmission?
16. Why do radio stations broadcast *modulated high-frequency* waves instead of waves that agree in frequency with the sounds in the studio?
17. Why is an adjustable resonant circuit usually connected to the antenna of a radio receiver?
18. Why is *detection* necessary in a radio receiver? Why would the incoming signal, even amplified sufficiently, not operate a loud speaker?
19. How is detection of the audible frequencies accomplished in a radio receiver?
20. For what reason do radio receivers require amplifier circuits?
21. What is the object of *scanning* a picture to be transmitted by television? How is scanning accomplished in modern television systems?
22. Why must very high frequency waves be used in the broadcasting of television signals?
23. What sort of apparatus is used in a television receiver for reconstructing the televised picture? How is it controlled?
24. On the radio page of your newspaper, the frequencies of broadcasting stations are probably listed in "kilocycles" for AM (ordinary broadcast) and in "megacycles" (million cycles per second) for FM and television. What are the wave lengths corresponding to listed frequencies from each of these three classes of broadcast?

CHAPTER XVIII

LIGHT AND THE ATOM

RADIATION AT HIGH TEMPERATURE

Most of the light energy which we use comes from incandescent materials—from the sun during the day and usually from glowing tungsten filament lamps at night. It is quite apparent that of the energy from lamps or the sun at least part has a "heating" effect. We might ask whether this has anything to do with the warmth that we feel when invisible radiant energy from a hot steam radiator or a hot stove strikes our hands.

What is this radiation which streams to us from hot objects and how does it travel—even through a vacuum?

Heat and Electromagnetic Waves. Let us look more closely at what happens when the temperature of an object is increased progressively. Suppose that we gradually heat a tungsten lamp filament by increasing the current in it. Then, at low temperatures we see no visible radiation but heat energy can easily be felt. As we increase the temperature to about 500°C, a dull-red glow can just barely be seen. With further increase of the current and the temperature, the filament grows ever brighter, first red, then yellowish orange, and finally at the highest temperatures it seems almost "white." This last means that finally the filament is radiating, in about sunlight proportions, all the frequencies which affect the retina of the human eye.

Our eyes are very limited in their response to radiation; that is, "visible" radiations range only from red to violet. Herschel discovered more than a century ago that, when the light from the sun is passed through a prism and thus spread out into the spectrum, a thermometer placed beyond the visible red region becomes very warm. Clearly then the visible spectrum is only a part of the spread-out energy stream, and it is customary to call that invisible part which lies next to the red the ***infrared***. When we expose

ourselves too long to bright sunlight, we get a fine sunburn which may be very painful, but if the sun's light passes through ordinary glass it gives no burn or "tanning" effect. Another invisible region beyond the violet end of the spectrum, the ***ultraviolet***, is responsible for sunburn. Most glasses are fairly opaque to ultraviolet radiation.

The general process of "temperature radiation" seems fairly reasonable if we remember the basic ideas of the kinetic theory, Maxwell's ideas about electromagnetic waves, and our general experience with radio waves. The atoms of all solids are in continual to and fro motion, with an average kinetic energy, $\frac{1}{2}mv^2$, which is proportional to the absolute temperature. All atoms are made of electric charges, and such vibrating electric charges continually send out electromagnetic waves. If the temperature is increased, the average energy of motion increases and the frequency of the radiated electromagnetic waves also increases.[1] At temperatures below about 500°C, these electric waves are invisible "heat waves" in the infrared region, but if the temperature is raised to a little above 500°C some of the vibration frequencies correspond to the longer visible waves—red (the extreme red frequency is about 3.8×10^{14} vibrations/sec, or the wave length is about 7.9×10^{-5} cm). As the temperature is raised a few hundred degrees further, yellow and even violet frequencies are radiated (the extreme violet frequency is 7.5×10^{14} vibrations/sec, or the wave length is about 4×10^{-5} cm). If the temperature can be made much higher, say 3000°C, considerable ultraviolet light of even higher frequency (and shorter wave length) is given off.

All experiments show that the only difference between infrared, visible, ultraviolet, and radio waves is that their frequencies are different. All these waves even travel in vacuum with the same speed, 186,000 miles per second or 3×10^8 meters/sec.

The Spectrum of Hot Objects. Physicists have long investigated the radiations from heated objects with the aid of such devices as prisms to "spread out" the wave lengths (often the prisms are of rock salt which absorbs little infrared light or of quartz which absorbs very little visible or ultraviolet light). Thermocouples, which are sensitive to radiant energy regardless of color, and photographic plates have been very useful to go beyond the eye's range of sensitivity.

[1] We shall see that radiation by *atoms* is actually more complex than these processes

The "color" or frequency distribution of the energy radiated by objects at various temperatures, Fig. 423, confirms what we were led to believe by our crude experiment with the lamp filament. The energy is all infrared at low temperatures, but with rising

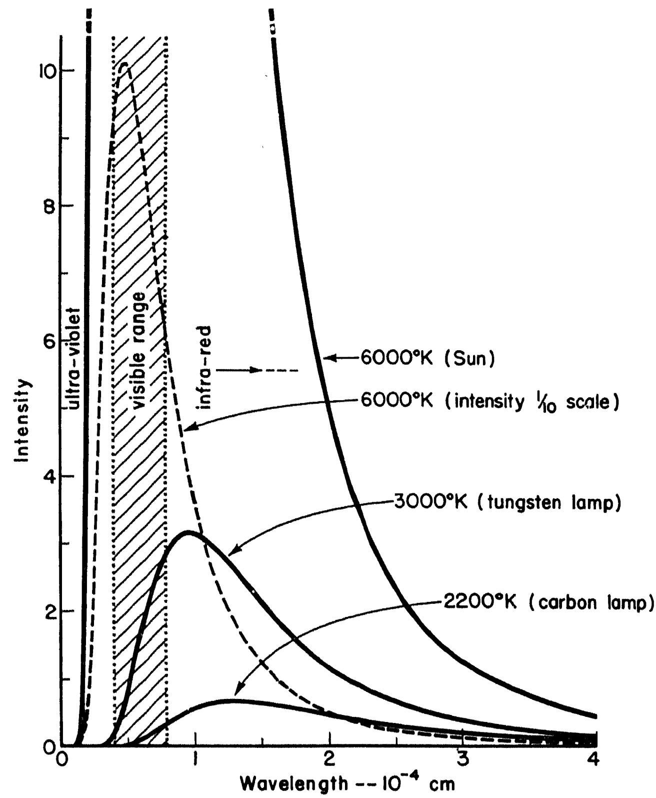


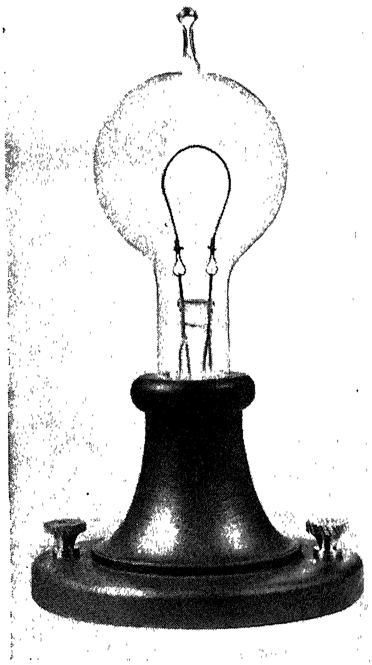
Fig. 423. Radiation from "black bodies" depends markedly upon temperature. At 3000° K, the temperature of a tungsten-lamp filament, only a small fraction of the total intensity of radiation lies in the visible region so the light efficiency is small. However, at 6000° K, the temperature of the sun's photosphere, an appreciable portion of the intensity is visible.

temperature the maximum moves progressively from the infrared toward the red and then toward the violet end of the spectrum. The spectrum is *continuous,* with no breaks—just a continuous gradation of frequency, or color.

Physicists usually compare distributions of this type to that which would be given off by an ideal "black body,"[1] or perfect radiator. Actually, most objects radiate almost exactly the same

[1] A truly black body also is a perfect absorber of radiation.

when at the same temperature, that is, they radiate almost like "black bodies." This is very convenient, because it means that the temperature of an incandescent object can easily be gaged from its color.



(*General Electric Company.*)

Fig. 424. Replica of Edison's first incandescent lamp. Carbonized cotton thread was used as a filament.

The amount of energy radiated per second by an object increases rapidly as the temperature is raised. Stefan discovered in 1879, and Boltzmann later showed theoretically that the energy radiated per second by a "black body" increases ***in proportion to the fourth power of the absolute temperature,*** which is very rapid indeed. The expression

$$\text{Energy radiated/sec} = \text{constant (temperature °K)}^4$$

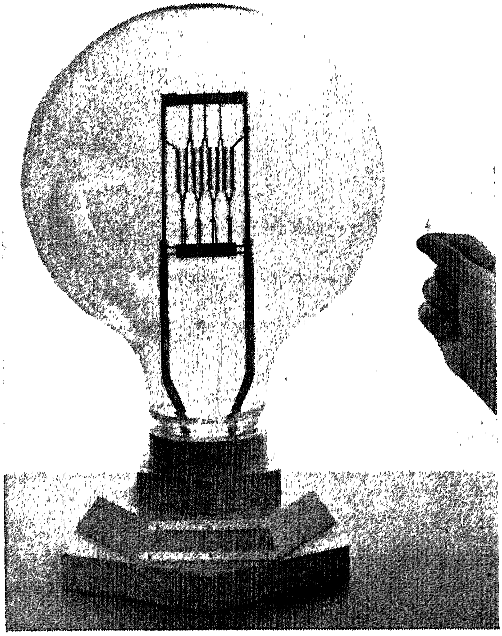
is usually called the Stefan-Boltzmann law. If an object does not receive back any of the energy it radiates, we see that, in order to double the absolute temperature of the object, sixteen times as much power must be used!

Incandescent Light Sources. The light from most man-made sources (tungsten melts at 3600°K) is at best a poor rival to that from the sun. The distribution of the energy radiated from the surface of the sun corresponds to the high temperature of 6000°K, and the maximum is in the yellow-green region. Perhaps for this reason the human eye has grown to be most sensitive to yellow-green light. With the sun such a source of light, we can be thankful that most of the ultraviolet light from it is absorbed by the upper atmosphere and by water vapor; otherwise we should all be tanned to a crisp.

In 1879, Thomas Edison capped a long and costly series of experiments with the first successful incandescent lamp. This lamp utilized a filament of carbonized cotton thread. The carbon lamp,

though inefficient on modern standards, opened a new era in lighting.

The luminous efficiency of an incandescent lamp, that is, the fraction of the power used that is radiated as visible light, increases

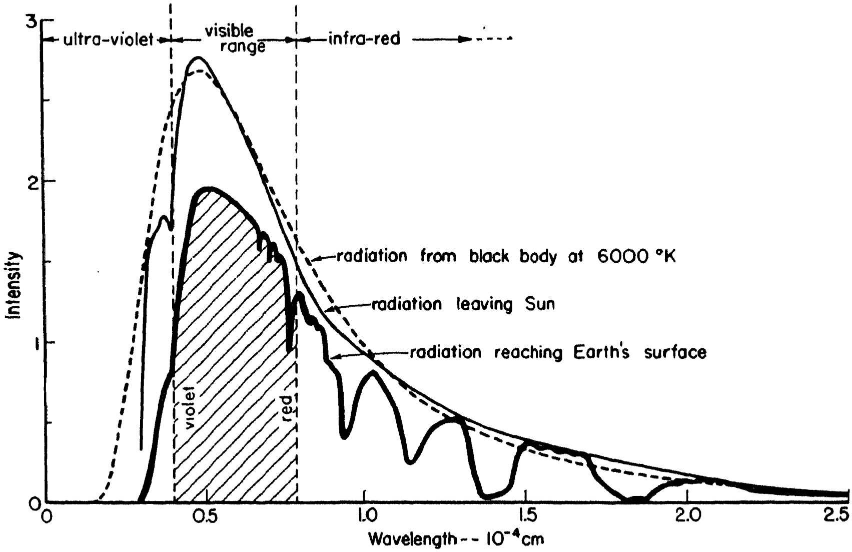


(*Westinghouse Electric and Manufacturing Company.*)

Fig. 425. Giant and pygmy lamps. A 5,000-watt airport lamp and a tiny ½-watt "grain-of-wheat" lamp used with surgical instruments such as bronchoscopes.

rapidly with temperature. However, as the rate of evaporation of the filament material also increases, the lamp "burns out" quickly at the higher temperatures. A compromise between life and luminous efficiency must be made. Tungsten has the highest melting point of all metals, 3600°K, and its introduction as a filament material permitted high operating temperature and luminous efficiency together with reasonable life. Such improvements as filling the bulbs with inert gases like argon, coiling the filaments into tiny spirals, and, recently, coiling the spiral filaments to make a double coil (coil-coil), have progressively increased the possible operating temperature for a given evaporation rate, or "life," so that the luminous efficiency of today's tungsten lamp is far higher than that of the first "hairpin in a bottle."

Even so, only about 10 per cent of the electric energy input to an incandescent lamp is radiated as useful light. The rest is converted into heat. Furthermore, the light is not truly "white," for the reddish portion of the spectrum predominates. Brute-force



(*After Abbott and Langley.*)

Fig. 426. Radiation normally received on earth differs markedly from the nearly black-body radiation leaving the sun. Fortunately for human beings the dangerous portion of ultraviolet light is largely absorbed in the upper atmosphere, giving rise to ionized regions there. Absorption due to water vapor and carbon dioxide in the atmosphere causes irregular depressions in the infrared.

methods of producing light by making the electric charges in the atoms vibrate at high frequencies by means of high temperatures are clearly not very efficient. Recent developments of "cold" or "fluorescent" lamps, which we shall discuss in another section, offer much more promise for real efficiency.

Measuring Star Temperatures. A clue to a method for measuring stellar temperatures may be found in Figs. 423 and 426, in the way in which the wave-length distribution of radiant energy varies with temperature of the radiating object. If the spectrum of a star is analyzed and allowance is made for absorption of light in the earth's atmosphere, the surface temperature of the star can be inferred from the position of the maximum and the form of the distribution curve. This assumes that the star is radiating like a

"black body." The so-called "red giants" like Betelgeuse have surface temperatures as low as 3200°C. Our nearest star, the sun, and others like Capella are at about 6000°C. Sirius, a very bright white star, is nearly 11,000°C, and the surfaces of some stars like δ Orionis are so hot, about 23,000°C, that their spectral maxima are far in the violet region and they appear blue-white.

Planck and the Quantum Idea. That vibrating electric charges in atoms at high temperature should radiate short-wave-length, high-frequency electromagnetic waves seems reasonable. However, all the early efforts by Lord Rayleigh, Jeans, and others failed to give a quantitative explanation of the form of spectrum radiated by a black body.

In 1901, Max Planck resolved the difficulty by introducing the revolutionary concept that light energy is emitted or absorbed only in individual units or ***quanta,*** the energy of which is proportional to the frequency of the light.

$$\text{Quantum energy} = h \times \text{frequency}$$

As we recall, h is a universal constant of nature, called "Planck's constant," and has the value 6.55×10^{-34} joule-second. The mathematics of Planck's solution is too involved to discuss here, but it is sufficient to say that, with this new idea as a basis, the form of the spectrum of a hot object (strictly speaking only a "black body") can be predicted very exactly for any temperature.

To many people, this assumption that light is emitted only in discrete "particles," quanta, or photons having a definite energy, rather than as continuous waves, seemed far-fetched and artificial. Nevertheless, as we saw in Chap. XV, Planck's quantum idea soon succeeded in describing the photoelectric effect. In all phenomena of radiation, the succeeding triumphs of the quantum theory have been so many and so extensive that it is now accepted universally.

RADIATION FROM ATOMS

Bright-line Spectra. When physicists first trained their crude spectroscopes on the luminous gas in low-pressure electric discharge tubes, and on materials vaporized by the high temperatures in electric arcs and sparks, they found sharp, distinct bright lines that were characteristic of the elements. This strongly contrasted with the continuous spectra radiated from solid bodies at high

temperatures. As we found earlier, the pioneer investigators Kirchhoff and Bunsen, by 1859 (see page 87) had described clearly the differences between such ***bright-line spectra*** from gases and vapors, where the individual atoms are quite free, and the continu-

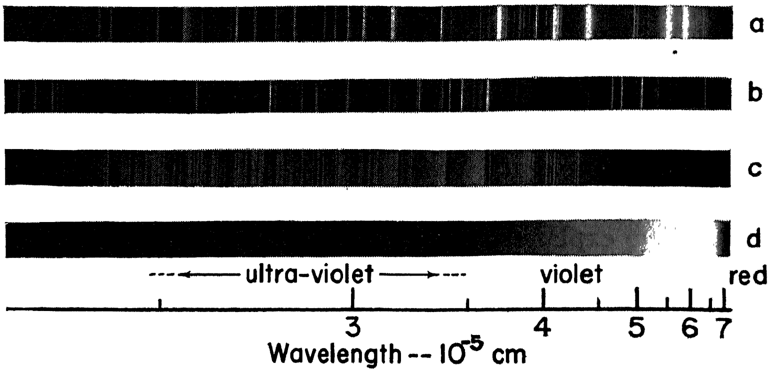


Fig. 427. Bright-line spectra in the ultraviolet and part of the visible region. (a) Mercury arc, (b) cadmium spark, (c) tungsten spark, (d) incandescent lamp (for comparison).

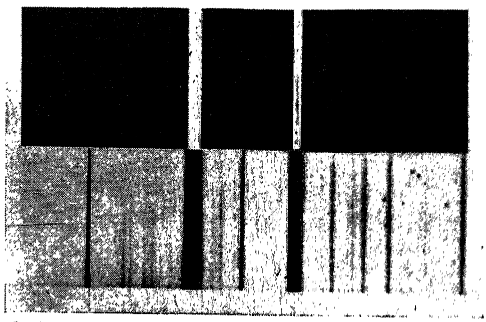


Fig. 428. Top: Bright-line spectrum (sodium D lines) from sodium source in laboratory. Bottom: Solar-absorption spectrum showing same two sodium lines (Fraunhofer lines).

ous spectra from incandescent solids or gases and liquids under high pressures, where the atoms are "bound" together.

Absorption Spectra. We recall that Fraunhofer, in 1815, discovered that the continuous spectrum of the sun has many black lines in it. Kirchhoff then found that this effect could be duplicated in the laboratory if white light, as from a carbon arc, passes through a layer of cool gas or metal vapor on its way to the spectroscope. The atoms of the cooler layer absorb the same characteristic frequencies

that they would emit if they themselves were "excited" in an arc or discharge. The stars have comparatively cool layers of the gases and vapors of their component elements outside their hot interiors; these act as absorbing or "reversing layers." Hence stellar spectra

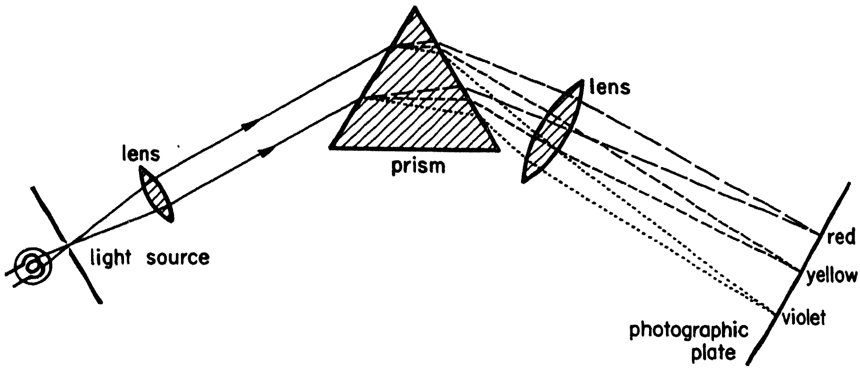


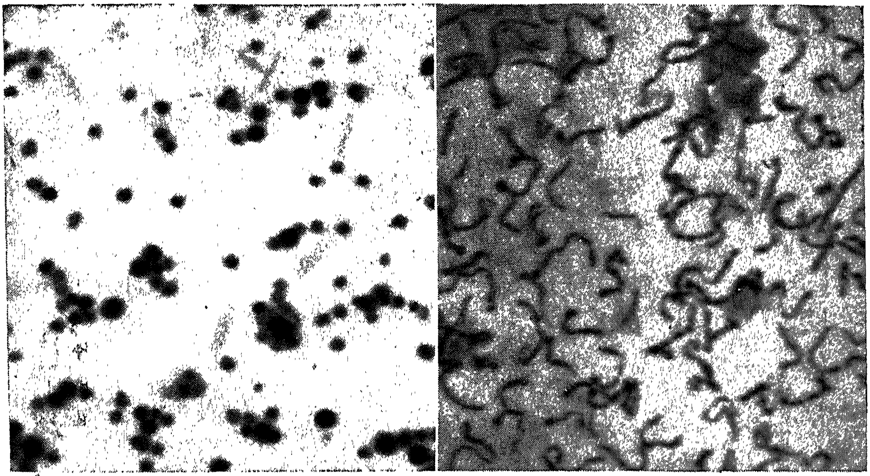
Fig. 429. Prism spectrograph—schematic. Light made into a parallel beam by a slit and collimating lens is separated into its component colors by a prism. The various frequencies present are brought to a focus at different points on the photographic plate.

exhibit black lines which identify the elements present. As our early glimpse of astronomy revealed, this discovery was a great aid to students of astrophysics.

Spectroscopy. Long before it was known *how* atoms emit characteristic frequencies, physicists, chemists, and astronomers recognized the need for careful study of the spectra of all the various elements. This was partly because such study promised to provide an extremely sensitive tool with which to identify elements and analyze materials. It was also realized that the frequencies present in a line spectrum must depend upon some structural details of the atoms concerned. Therefore, all the knowledge possible was acquired about these spectra in the hope that it would yield clues which eventually might be pieced together to give a picture of the interior of atoms. Thus, catalogues of the wave lengths of the spectral lines from the different elements were built up by much careful work.

TOOLS OF THE SPECTROSCOPIST

Numerous refinements in spectroscopes have made them more accurate than those of Kirchhoff and Bunsen, and have spread out the spectrum to reveal much finer detail. By photographing the



(a) (b)

(*Photo Technique.*)

Fig. 430. Electron microscope reveals structure of extremely fine grain photographic emulsion. (a) Undeveloped grains of Lippmann emulsion composed of colloidal silver bromide. (b) Developed Lippmann emulsion showing how each tiny crystal has lengthened into a wormlike thread. (Magnification 50,000 diameters.)

spectral lines, it was possible to keep permanent records and at leisure make accurate measurements of line positions. We recall that prisms of quartz or fluorite which transmit the ultraviolet radiation well, and of rock salt which transmits radiation of the infrared region, have been used to extend spectral investigations beyond the limits imposed by the human eye.

Gratings and Interference. Probably the most convincing proof of the wave nature of light came about 1800, when Thomas Young demonstrated that two beams of light from the same source can be made to "interfere," sometimes canceling and sometimes reinforcing one another. In any wave motion, if the crests of one wave coincide exactly with the crests of another of the same amplitude, the resulting wave has twice the original amplitude (Fig. 431*a*). If the "crests" of one and the "troughs" of the other coincide, the two waves cancel, or interfere destructively (Fig. 431*c*). Young showed that if the light from a single source passes through two pinholes, the effects will cancel if the paths traversed by the waves from the two pinholes differ in length by a half wave length (or an odd multiple of a half wave length), and they will reinforce

if the path difference is a whole wave length (or any whole multiple of one wave length).

Out of these experiments came a great aid for spectroscopy, introduced in the form of Fraunhofer's first crude "grating," and

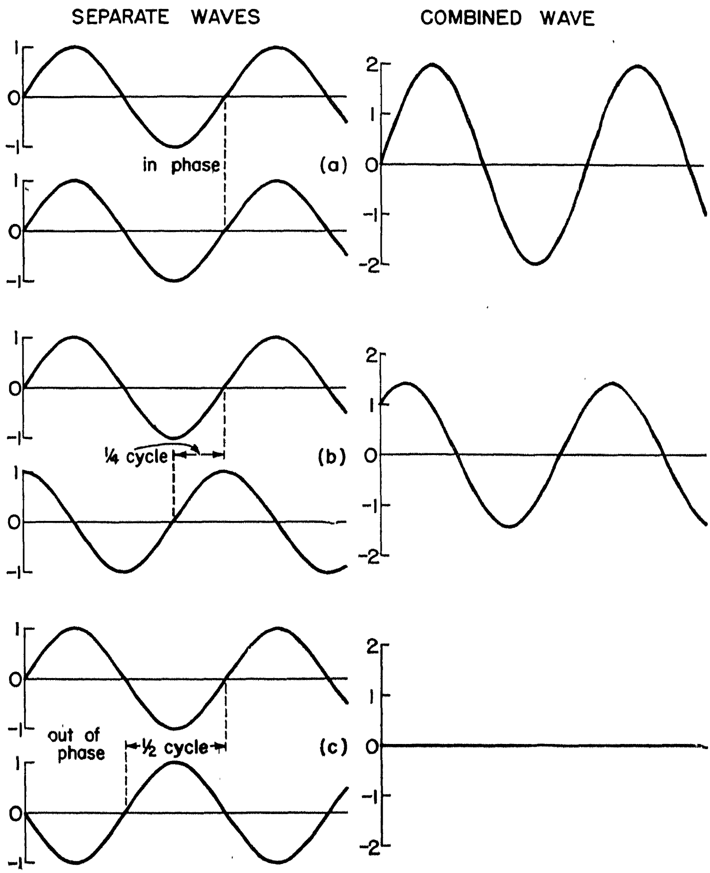


Fig. 431. Constructive and destructive interference of two similar waves. (a) Where the waves come together with crest over crest (i.e., in phase), they combine to give twice either original amplitude. This is constructive interference. (c) Where crests of one are over troughs of the other (i.e., they are out of phase), the effects cancel one another, giving destructive interference. (b) Intermediate shifts between the two waves produce intermediate resulting amplitudes.

greatly improved later, especially by Rowland in America. The principle in this instrument is essentially the same as in the experiment of Young, except that there are very many "slits." Modern gratings are made by ruling on a piece of glass or metal with an

extremely fine diamond point many parallel equidistant lines, perhaps 20,000 per inch.

Figure 433 illustrates the interference of light which has been *diffracted* or "fanned out" (see Fig. 434) by the various "slits"

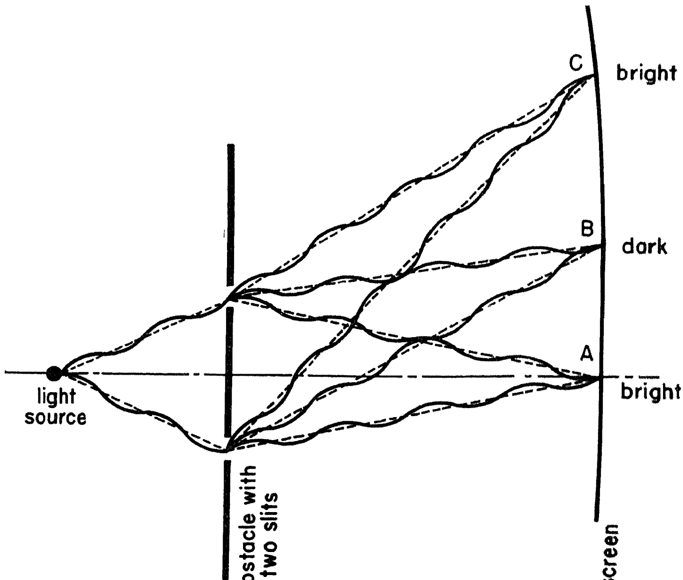


Fig. 432. Interference of light from two slits—schematic. Light waves that meet at position A on the screen have traveled the same distance from the source and so arrive in phase (since they left the source as a single wave and therefore had to be in phase then). Thus these waves interfere constructively and give a bright region. At position B the lower wave has traveled one-half wave length farther than the upper, and so the two waves arrive out of phase, interfere destructively, and leave a dark region on the screen. At C the path difference for the two waves is a whole wave length and so there the waves arrive in phase and another bright region results. Interference between light from the two slits, then, produces on the screen a series of separate bright bands parallel to the two slits.

of a glass grating. For the direction chosen, the distance *d* (Fig. 433*b*), is the difference in length of the paths of light from two adjacent slits. Light of the wave length that is just equal to *d* (or for which a whole number of wave lengths equal *d*), then is reinforced along the direction indicated. Other wave lengths are reinforced along directions which are generally different, so that a spectrum of the various wave lengths from a light source is spread out and may be photographed.

Large reflecting metal gratings with perhaps 200,000 lines are usually made concave to "focus" the spectrum, so, like a concave

objective mirror of a reflector telescope, no lenses are needed for photographic purposes. With some gratings of this type the light

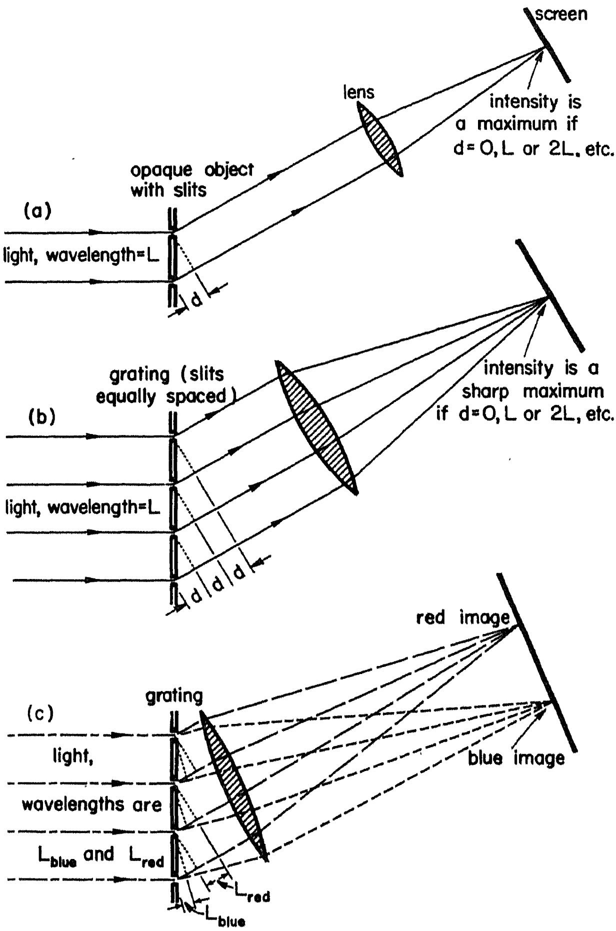
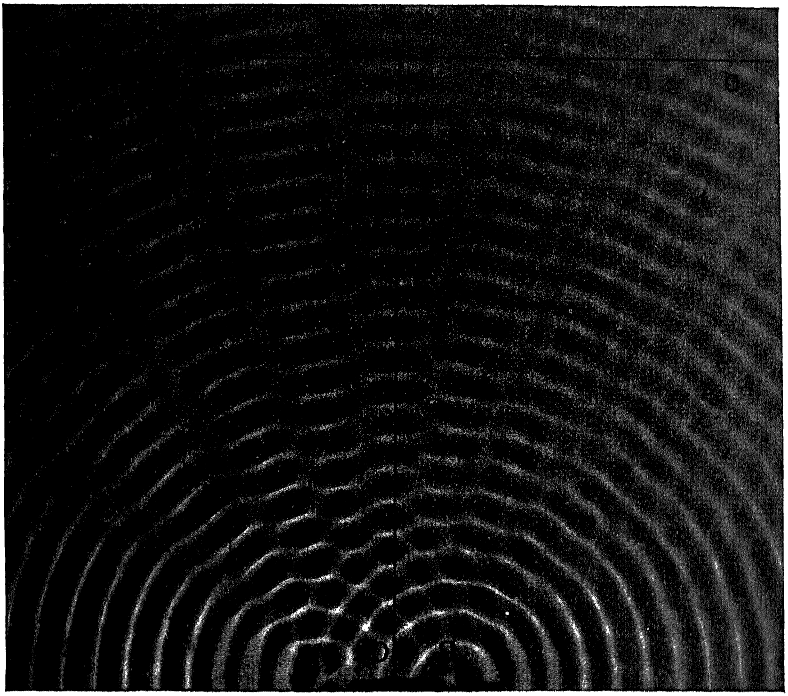


Fig. 433. Diffraction grating. (a) From Fig. 432, a double slit gives maximum intensity for monochromatic light where the path difference for the two rays, d, is zero or a whole number of wave lengths. (b) A grating of many equally spaced slits gives maximum intensity at the same places as a double slit of the same spacing. However, the effects of all adjacent pairs of slits add together to give sharp bright lines instead of the broader bands of the double-slit pattern. (c) The positions of maximum intensity from a grating depend upon the wave length of the light. Thus if several wave lengths (i.e., colors) are present, they give bright lines at different places on the screen and thus form spectra of the light used.

may be spread out in a spectrum along a semicircle 30 ft in radius. This permits the examination of very fine detail of the spectral lines. Furthermore, by knowing the spacing of the lines of the

The spectroscope makes such a sensitive and convenient tool with which to identify atoms and molecules that it is being called upon more and more, not only in physics, but in chemistry, biology, metallurgy, many industries, and even scientific crime detec-

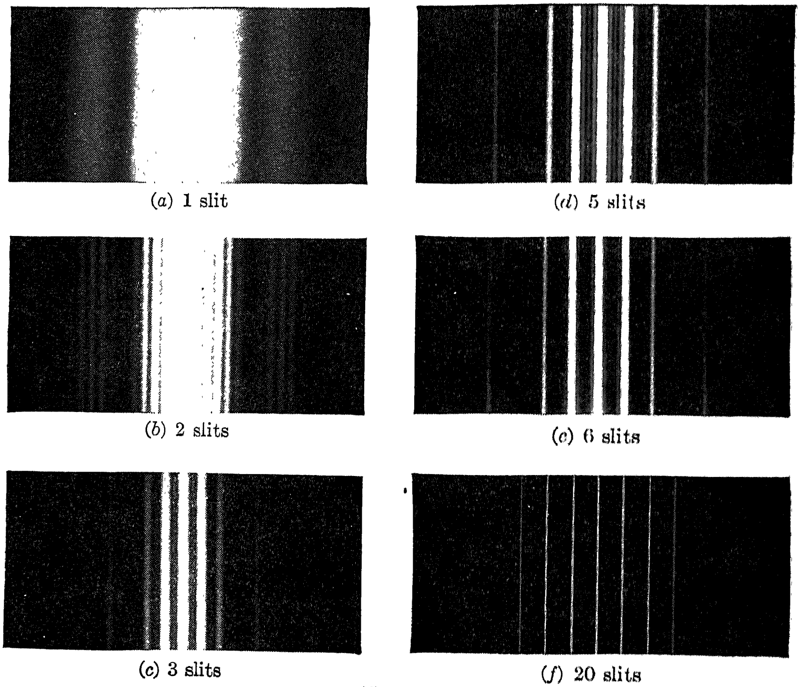


(*Webster, Farwell, and Drew, General Physics, Appleton-Century.*)

Fig. 435. "Double-slit" interference of water waves. Destructive interference effects appear along well-defined divergent lines. About halfway between these lines there is constructive interference.

tion. Ordinary chemical analysis requires a comparatively large amount of material and is usually laborious and time consuming. If a tiny quantity of material to be tested is vaporized in the intense heat of a 4000°C electric arc or in a spark, and if the emitted light is photographed by a spectrograph, all the atom types present leave their telltale lines on the plate. The elements can be easily identified in a few minutes by comparing the line wave lengths with lists in wave-length catalogues. Furthermore, the relative blackening of the lines usually indicates the percentage composition with fair accuracy, and even traces of impurities may be discovered readily.

In case of doubt, ask the spectrograph. Is the patient suffering from lead poisoning? If so, a drop of blood vaporized in an arc will show the incriminating lead lines on the spectograph plate. What is the composition of the new alloy produced by your competitor?



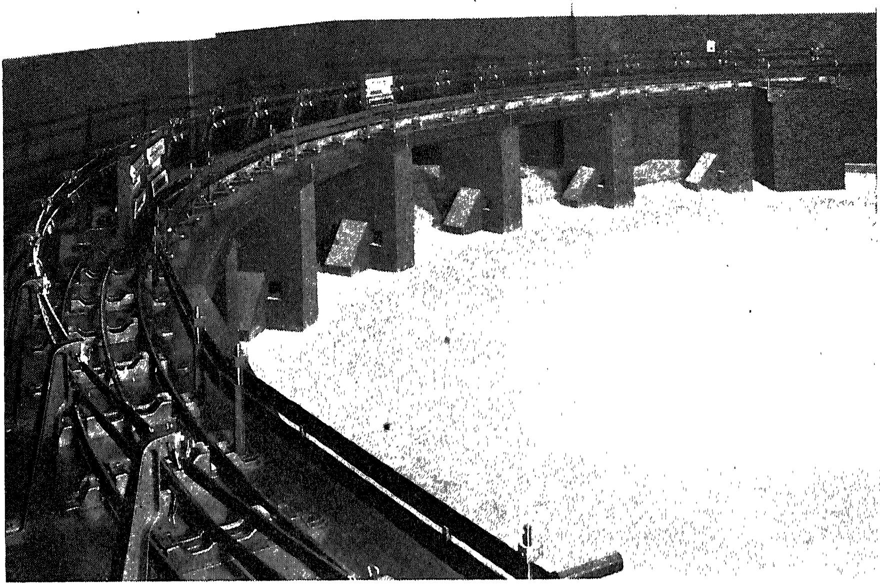
(*Jenkins and White, Fundamentals of Physical Optics.*)

Fig. 436. Diffraction patterns for gratings containing various numbers of equidistant slits. The "lines" of the patterns become sharper as the number of slits is increased.

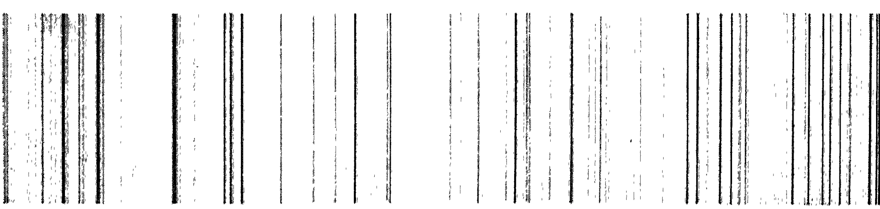
The spectroscope will tell you quickly. Is there an excessive amount of arsenic spray on the fruit in this shipment? The spectograph will answer this, too. Did the small specks of paint left on the victim killed by a hit-run driver really come from the fender of the suspect's car? The spectroscope will easily establish or disprove the charge.

"DECODING" ATOMIC SPECTRA

The spectrum of a complex atom like iron is exceedingly intricate, for at least 20,000 component lines may be seen. The spectroscope, however, reveals that when a simple atom like hydrogen emits light the spectrum is much less intricate. The regular succes-



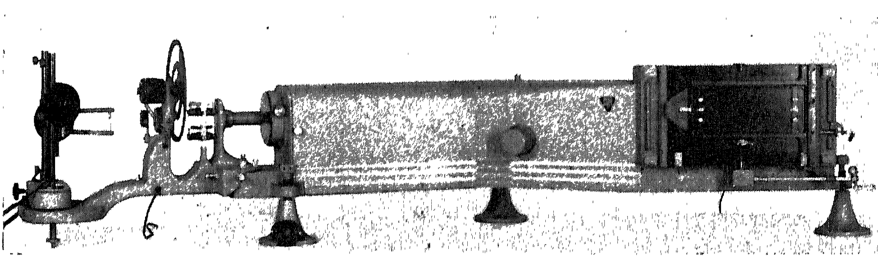
(a)



(b)

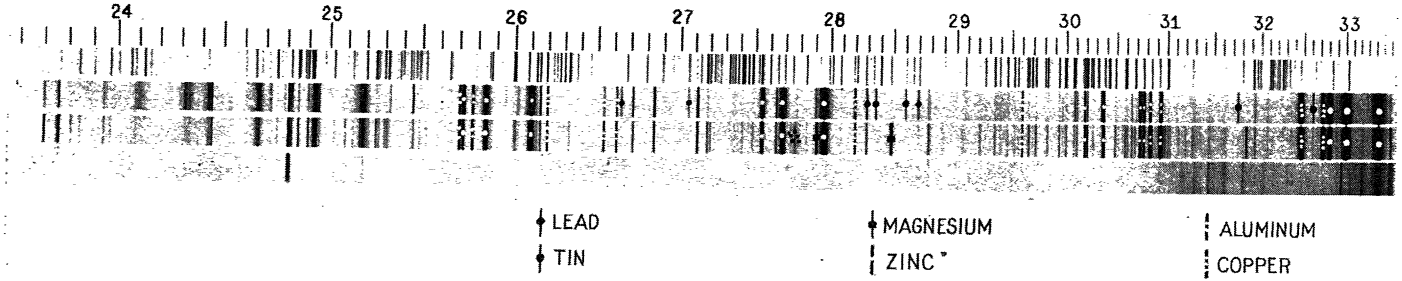
(*George R. Harrison, Atoms in Action, Morrow.*)

Fig. 437. (a) Large grating spectrograph. Spectrum is spread around circle stretching a hundred feet. Photographic plates are clamped on track to photograph desired portion of spectrum. (b) Small portion of iron spectrum, showing a few of many thousands of lines emitted by excited iron atoms.



(*Bausch and Lomb Optical Company.*)

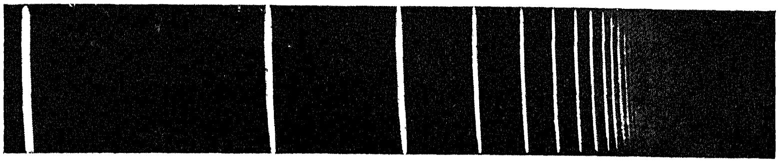
Fig. 438. Quartz prism spectrograph. Light source is at left and photographic plate holder at right.



(*Bausch and Lomb Optical Company.*)

Fig. 439. The spectrograph analyzes alloys. The central pair of spectra are of two die-casting alloys (of the 93 per cent zinc, 4 per cent aluminum, 3 per cent copper type), the lower of good quality, the upper, one that failed in service. Note the presence of excessive amounts of tin and lead in the defective alloy and the absence of magnesium, a beneficial constituent of the good alloy. The top spectrum is of iron, for reference purposes, the bottom of graphite electrodes.

sion of the lines in a spectral ***series,*** such as the one from hydrogen illustrated in Fig. 440, gave the first clue to atomic structure. Balmer discovered that a simple numerical expression would give



(*Herzberg.*)

Fig. 440. Balmer series of hydrogen.

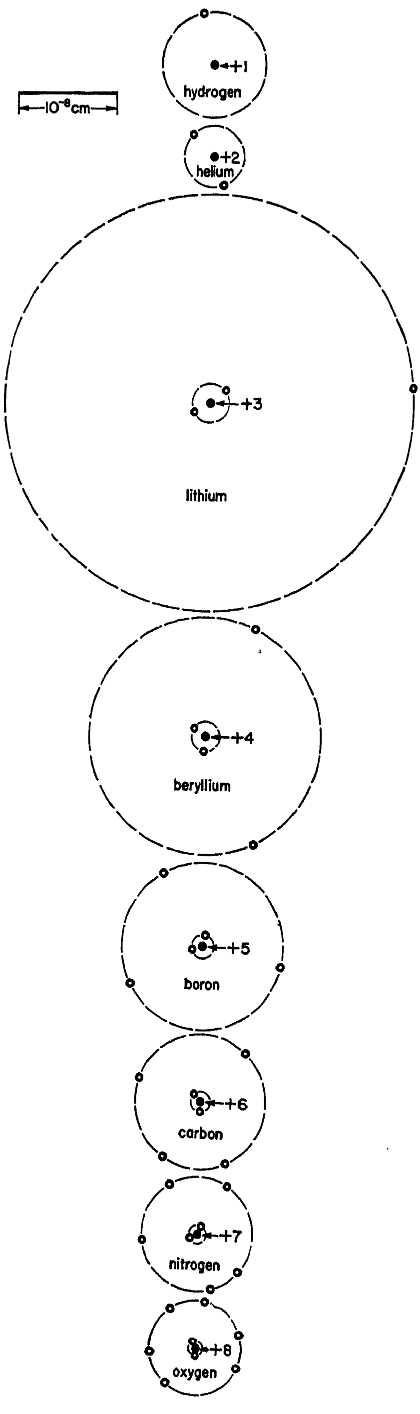
the correct frequencies of the lines of the series illustrated. With an up-to-date value of the constant, it is

$$\frac{\text{Frequency}}{\text{Velocity of light}} = 109678.3\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

Here it was only necessary to let $n = 3, 4, 5, 6, \cdots$ to get the correct frequency values for all the lines of this series. Several other similar series were discovered later in the ultraviolet and infrared parts of the hydrogen spectrum, and in spectra of other light elements.

For many years the secret of atomic structure which lay behind these simple relationships remained unfathomed.

The Rutherford-Bohr Atom Model. In 1913, Nils Bohr, then a young Danish physicist studying in England, built the framework of our modern atomic theory. Sir Ernest Rutherford had just laid the foundation for this work by his experiments on firing alpha particles at atoms in a thin foil (see Chap. XX), which showed that the atom consists of a tiny but relatively heavy positively charged central core, or nucleus, with light electrons revolving about it (much like a miniature solar system), as was pointed out before. Rutherford and Bohr proposed that the hydrogen atom (atomic number 1) must be made up of one positively charged nuclear particle, which we now call the ***proton,*** with one negative electron revolving around it to make the atom electrically neutral. The electron was supposed to be held in its orbit by the electrical attraction of the oppositely charged nucleus, rather than by gravitational attraction as in the case of the planets and the sun. Likewise,



the helium atom (atomic number 2) must have two positive charges on its nucleus and two outer electrons. Models of all other heavier atoms can be built up on a similar basis.

If atoms of this type follow the mechanical laws which Newton developed for much larger objects, any radiation process should give continuously distributed frequencies instead of sharp "lines." So Bohr concluded that our ordinary laws of mechanics must be modified in order to apply to tiny atoms. He reasoned that since this modification must account for *discrete* frequencies and since the quantum idea of light means that light energy comes in *discrete* "bundles," might not the application of the quantum idea to the motion of an electron in an atom be just what is needed to explain the radiation of *discrete* "bundles" of energy (hence, sharp spectral lines)? Thus, Bohr suggested that the electron in an atom can exist only in certain special orbits which are determined by quantum requirements on the motion

Fig. 441. Approximate relative sizes of electron shells of the eight lightest types of atom. This diagram is only a rough representation because electron "orbits" are now considered to be just average regions occupied by electrons. Even on the enormous scale at which the orbits are shown, electrons (white) and nuclei (black) should be several thousand times smaller than represented!

of the electron.[1] In the case of the hydrogen atom, for example, the smallest of these "allowed" orbits is the electron's normal orbit.

Bohr then made use of Planck's relation for the energy of light quanta, energy = $h \times$ frequency, to complete the picture in the

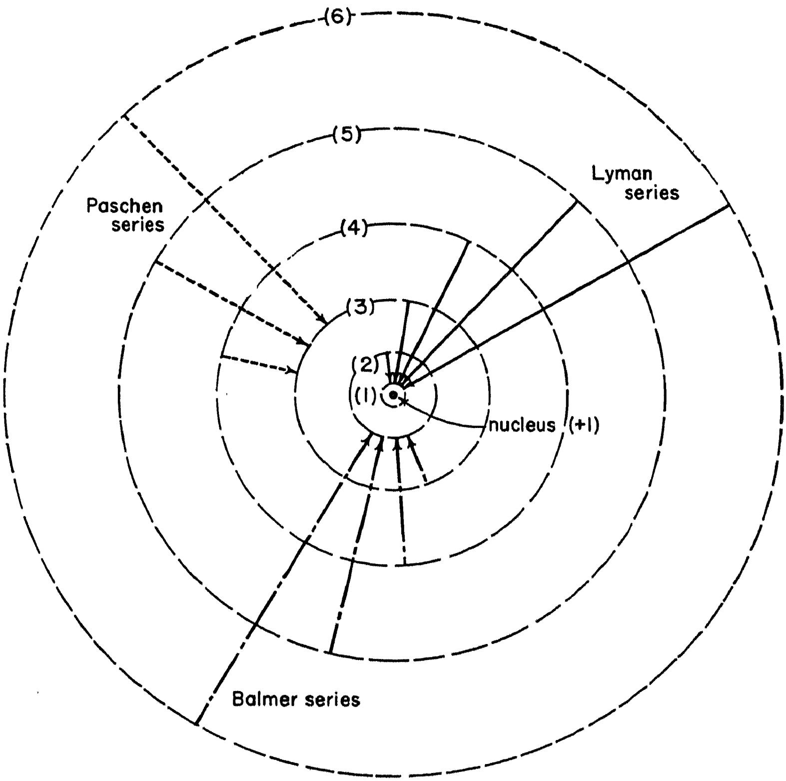


Fig. 442a. Bohr's original concept of allowed "orbits" in the hydrogen atom. The electron transitions represented by the arrows give rise to groups of spectral lines known as the Lyman, Balmer, and Paschen series.

following way. Now, if in such an atom the electron in its normal inner orbit is given more energy by being "hit" with another electron, with a positive ion, or with a photon, it will be transferred to one of the "allowed" outer orbits (unless it is completely knocked out of the atom, leaving an ion). The energy of the electron in one of these outer orbits must be greater than before by a

[1] Bohr expressed this by saying that the electron *angular momentum* could only be integral multiples of $h/2\pi$, where h is Planck's constant.

certain definite amount. We therefore say that a Bohr atom can have only certain "energy states" and no others. If an electron

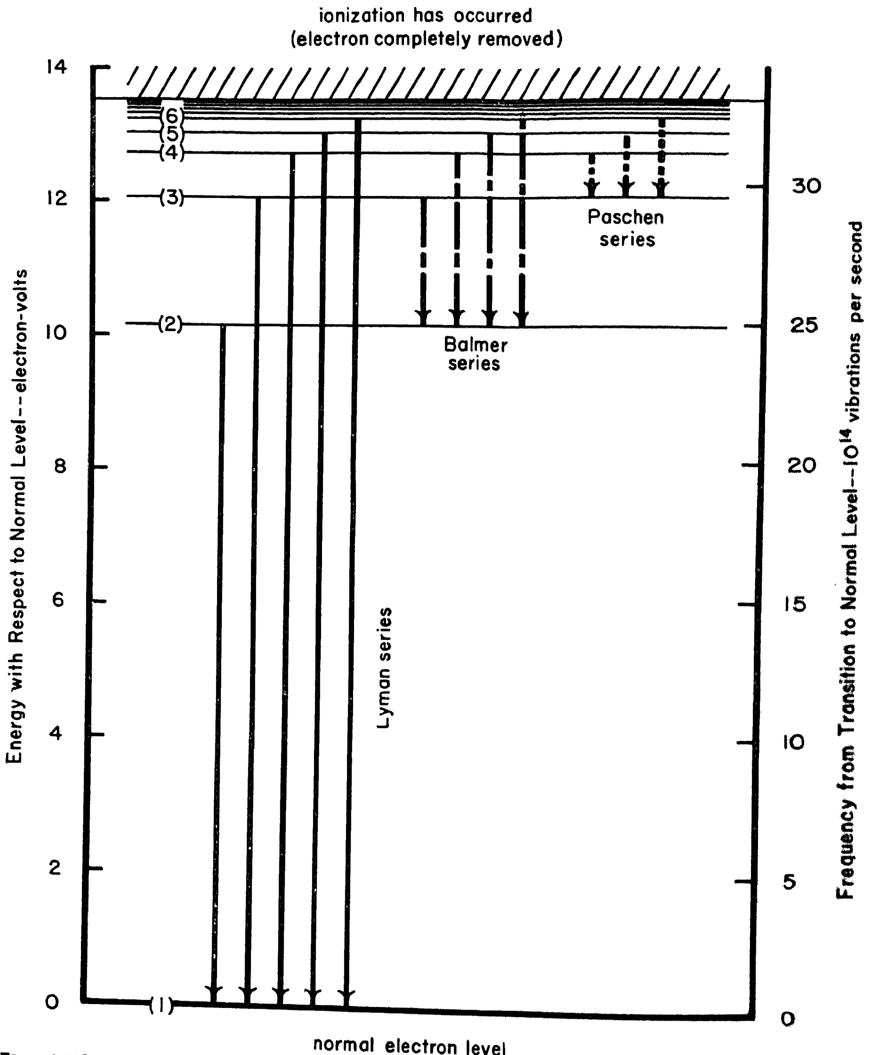


Fig. 442b. Energy changes corresponding to the electron transitions represented in (a). Each energy level corresponds to one of the oribits of (a), being the energy lost by an electron returning from that orbit to the normal (smallest) orbit. For the energy called the electron volt, see Chap. XX.

has absorbed energy and "jumped" to an oversize outer orbit, it can come back to its normal inner orbit only by "jumping" from

the outer to the normal orbit in certain definite possible steps by way of intermediate orbits. The energy given up by an electron when it makes a direct transition (in a single step) to any inner orbit is then radiated as a light quantum with a frequency which

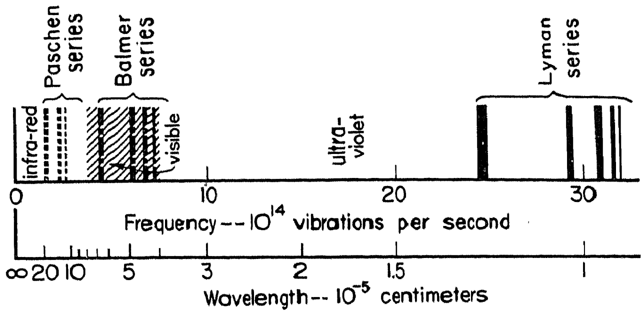


Fig. 442c. Frequency spectrum showing lines of the Lyman, Balmer, and Paschen series, which correspond to the transitions of (a) and (b). The Balmer series was discovered first because it is the only one lying in the visible region.

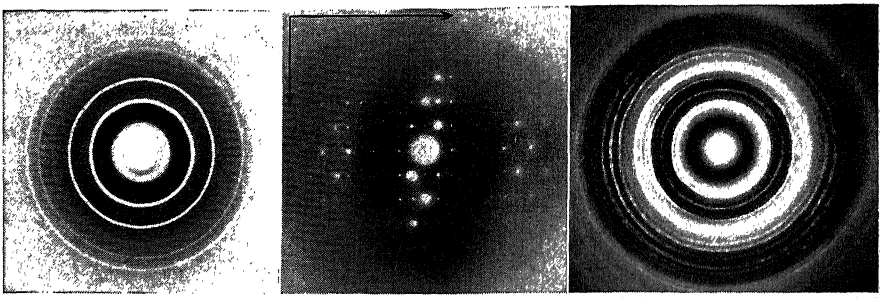
follows from Planck's relation.

$$h \times \text{frequency} = E_2 - E_1$$

where E_2 is the energy in the oversize orbit and E_1 the energy in the orbit to which the electron "jumps."

As suggested in Fig. 442*a*, the electron of a hydrogen atom may "fall downstairs" to its normal inner orbit in many ways, and the particular steps which give rise to two of the hydrogen series are indicated. Bohr's great triumph was to show that his theory of the hydrogen atom gave simple formulas for the positions of the lines in the various series, and that experimental observations checked almost perfectly with the theory. For example, Bohr's calculations agree precisely with Balmer's empirical formula for the visible series from hydrogen.

Just as in the case of planetary theory, refinements were added later to Bohr's atomic theory which made it account for certain spectral details. Among these modifications was one by Sommerfeld, the introduction of elliptical as well as circular orbits. Bohr's model gave good results for the spectra of the ionized helium atom and of several other simple atoms, as well as for that of hydrogen, although difficulties in calculation were encountered when it was applied to more complex atoms.



(*L. H. Germer.*) (*b and c, L. H. Germer and K. H. Storks.*)

(a) (b) (c)

Fig. 443. Electrons have wave properties. (a) Electron diffraction pattern produced by a sodium fluoride film about one-millionth of a centimeter in thickness. (b) Electron diffraction pattern from a single crystal of stearic acid. (c) Electron diffraction pattern produced by sharply oriented crystals of an aluminum soap. See X-ray diffraction patterns, Fig. 455.

ELECTRONS AND WAVES

We have seen how the continuous wave theory of light was modified by Planck with the interpretation that light consists of individual concentrated "lumps" of wave energy which we call quanta or photons. Thus the concepts of waves and particles were merged.

Davisson and Germer in 1925 startled the scientific world by showing that electrons, which had always been considered "particles," also have the properties of waves! They discovered that electrons showed the characteristic wave property of interference—just like light waves. The electron frequency was found to be proportional to the speed

$$\text{Frequency} = \frac{\text{mass} \times (\text{speed of electrons})}{h \times (\text{speed of light})}$$

This proof of the dual nature, or particle-wave nature, of electrons has since been verified in many ways. Now, in fact, all the so-called particles of which matter is built, such as protons, seem to have the properties of both particles and concentrated lumps of wave energy.

The New Quantum Mechanics. The Bohr atom model with its mechanical picture of orbits has now been reinterpreted in terms of a more mathematical description to which Schroedinger, Heisenberg, Dirac, and many others have contributed. In this new description, an electron orbit is interpreted as being just the most

probable position of the electron. Consequently, nothing is said about the position of any single electron—only the average position of a great many electrons in the same "state" is specified.

The Uncertainty Principle. In applying new, essentially mathematical ideas such as the wave description of electrons, the new quantum mechanics has stimulated many interesting innovations in philosophical thought. The "uncertainty principle" of Heisenberg emphasizes the uncertainty in the result of a measurement introduced by the influence of the very act of observation. For example, we see an object essentially by shining light on it and allowing an image to be formed in our eye by the light quanta reflected from the object. In general, when a large object is being observed, the effect of bouncing the light quanta off it is very small. On the other hand, if we were to attempt to observe one tiny electron by letting even a single light quantum fall on it and be reflected, the reaction of the bouncing quantum would always affect the electron's velocity and thus its position. Consequently, it is impossible to obtain both the position and velocity of an electron beyond a certain precision, and the uncertainty in the best possible measurements falls within rather definite limits which Heisenberg formulated.

You might think that it is bad to introduce this "haziness" into physical theory. Actually, however, by taking into account the uncertainties of physical observation, especially in the case of the atom where they may be important, we no longer fool ourselves about the preciseness of details and so we arrive nearer to a useful ***statistical*** description of atomic phenomena. The realization that the behavior of a single particle such as an electron can be predicted only on the average, that is, on the basis of probability, actually has extended the usefulness of the theory of atoms instead of limiting it.

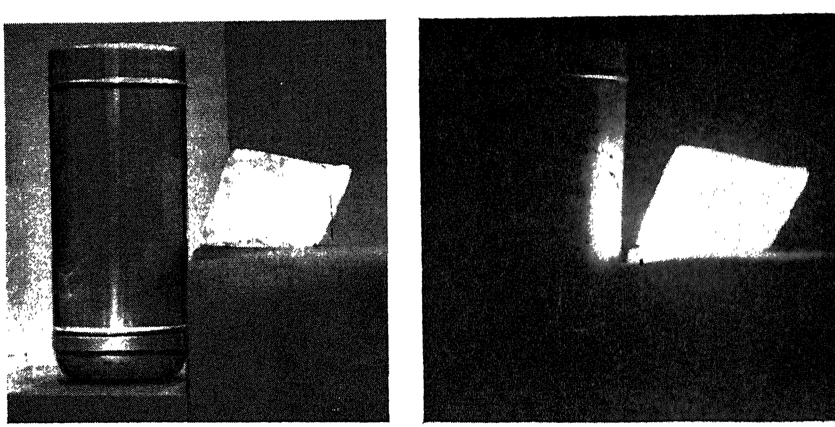
The extension of ideas about the uncertainty in behavior of individual electrons, in an attempt to answer philosophical questions concerning cause and effect, free will, etc., has had interesting repercussions, but the validity of such extrapolation must certainly be questioned.

The newer quantum mechanics has so far been remarkably successful in throwing new light on virtually all atomic phenomena to which it has been applied. The spectra of even the more complicated atoms and molecules have been interpreted with astonishing

consistency. The conduction of electrons in metals, the existence of magnetism, the structure of gases and solids, and even such chemical effects as the combining of atoms to form molecules, have all been treated with conspicuous success. Furthermore, new applications are continually appearing. In some cases, the mathematics may be too complicated to solve completely, but it appears safe to say that so far no experiments have been performed to which the quantum theory seems fundamentally inapplicable.

FLUORESCENCE AND PHOSPHORESCENCE

Many dull and prosaic-appearing minerals and compounds have long been known to glow with strikingly brilliant colors when illuminated by ultraviolet light. This effect, which is called ***fluorescence,*** is particularly impressive when "black light" is used—that is, when the source of light, such as a quartz mercury arc, is covered with a special filter-glass which lets through the ultraviolet light but absorbs all the visible light. Then the fluorescent materials glow eerily in the dark.



(a) (b)

Fig. 444. Fluorite (a) in ordinary light and (b) in ultraviolet light.

Many fluorescent substances cease glowing almost immediately when the ultraviolet light is shut off, but others continue to glow with gradually diminishing intensities, even for long times afterward. The latter are said to be ***phosphorescent,*** but actually it is not possible to make a sharp distinction between the two types of fluorescence.

The light emitted by fluorescing materials is *lower* in frequency than the light that causes the effect, in all normal cases. What is happening can be understood quite readily from what we have learned about the Bohr atom model.

We know from Planck's relation

$$\text{Energy} = h \times \text{frequency}$$

that a comparatively high frequency ultraviolet-light quantum has more energy than a quantum of visible light. Such a quantum can be absorbed by an atom or molecule of a fluorescent substance, and when the atom or molecule comes back to normal it may do so in two (or more) small steps, so that the absorbed energy is distributed between two (or more) emitted quanta which may be of visible frequency. Thus invisible ultraviolet quanta may be converted into quanta to which our eyes are sensitive. Sometimes an electron on its way back to normal may stay for a comparatively long time at one of the steps, giving rise to a delayed phosphorescent effect. Comparatively high energy electrons striking fluorescent materials, as the screen of a cathode-ray tube, can also produce the same effects.

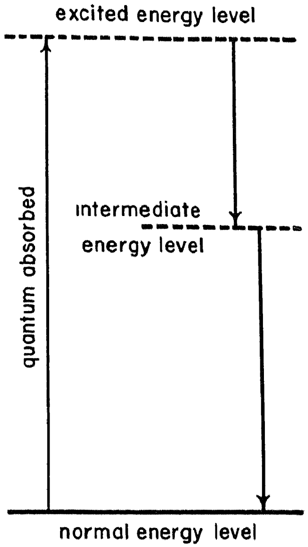


Fig. 445. Energy changes involved in fluorescent emission. An atom absorbs a comparatively high energy quantum, i.e., invisible ultraviolet quantum, and emits two quanta of lower energy which may be visible.

Fluorescent Lamps. Fluorescent effects have recently become of very practical importance through their application in the fluorescent lamps which are now being adopted widely because of their high efficiency and "white," or "daylight," quality. A mixture of several fluorescent materials, usually selected to give a combination of colors approximating "white," is first coated on the inside of a long round tube, which has electrodes on both ends. When a mercury discharge is started in a small amount of mercury placed in the tube before evacuation, the strong ultraviolet lines produced by mercury cause fluorescence of the materials coating the walls, and we see the resulting visible light. The ultraviolet light does not get out, for it is absorbed by the coating and the glass. Nearly any

desired color may be produced by proper choice of fluorescent materials.

The efficiency of such light sources, where the light is emitted by excited atoms and molecules, is very much higher than that of

(*Westinghouse Electric and Manufacturing Company.*)

Fig. 446. Office with indirect fluorescent lighting installed flush with soundproof ceiling.

the older incandescent lamps which depend only on high temperatures to produce light. A 15-watt fluorescent lamp usually emits as much light as a 40- to 60-watt hot filament lamp, so it gives much more nearly "cold" light with comparatively little radiation of unwanted "heat rays." Furthermore, the effect is usually more pleasing since the light is whiter and also more diffuse. More and better light at less cost—thanks to research on atoms.

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SUMMARY

An incandescent object radiates a continuous range of frequencies, including the ***infrared,*** the ***visible*** (from red to violet), and the ***ultraviolet*** regions. This electromagnetic radiation is given off by the vibrating atomic charges within the material. The higher the temperature, the higher the average frequency radiated.

The energy radiated per second by a "black body," or perfect radiator, is proportional to the fourth power of the absolute temperature. All "black bodies" have the same spectrum at a given temperature, and most other objects radiate similarly. The sun's spectrum (6000°C) has a maximum intensity in the yellow-green region and much of its ultraviolet light is absorbed in our atmosphere. Most of the energy from incandescent lamps is in the infrared, so their ***luminous efficiency*** is low. A star is assumed to have the temperature corresponding to the matching "black body" spectrum. The form of a black body spectrum could not be accounted for until Planck introduced the quantum theory of light.

The lines of bright-line (or of absorption) spectra are characteristic of the emitting (or of the absorbing) atoms which give rise to them.

Spectrographs may be used in the ultraviolet region with quartz or fluorite prisms and in the infrared with rock salt prisms. Spectra also may be produced by the Fraunhofer grating.

Heavy atoms have very complex spectra, but a light atom like hydrogen exhibits simple series of lines. Balmer found that the frequencies of one hydrogen series were given by a simple numerical expression, which remained uninterpreted until Rutherford and Bohr proposed their atom model. Bohr pictured the atomic electrons as existing in definite orbits about a relatively heavy posi-

tively charged nucleus. When an electron falls from a large orbit into a smaller one, its excess energy is radiated as a quantum of light with frequency given by: excess energy = $h \times$ frequency. Bohr's theory led precisely to Balmer's formula and interpreted equally successfully other spectra from simple atoms.

In 1925 Davisson and Germer showed experimentally that electrons, previously called particles, also exhibit the typical wave property of interference.

The original quantum theory of the atom has been reinterpreted so that an orbit now represents the ***most probable electron position.*** This actually has increased the scope of the theory. Involved in this interpretation is Heisenberg's ***uncertainty principle.***

Fluorescent materials absorb quanta and emit the energy at lower frequencies. ***Phosphorescence*** applies to appreciably delayed fluorescent emission. The fluorescent lamp makes use of this effect to obtain increased luminous efficiency.

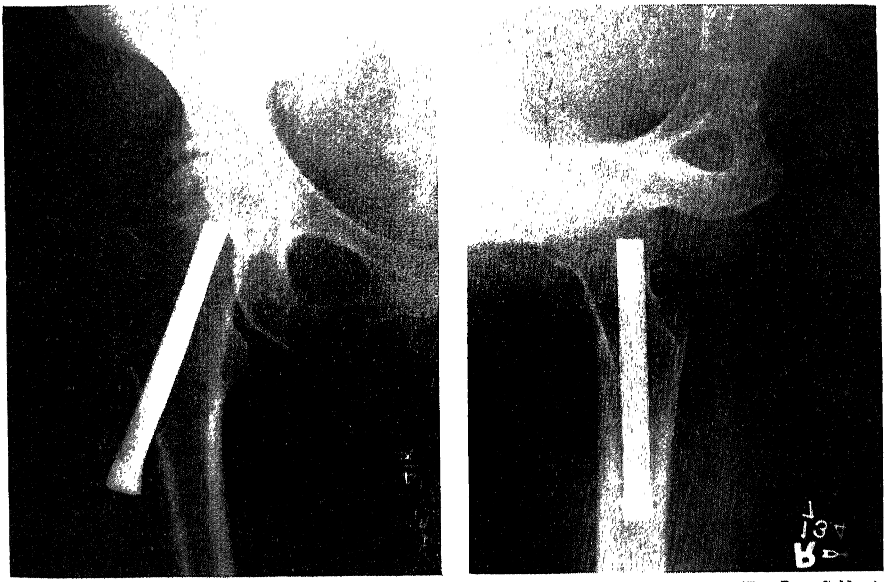
QUESTIONS

1. How does the kinetic theory help to account for temperature radiation?
2. What is "black body radiation"? How do its characteristics change with temperature?
3. What are the relative merits of dark paint and aluminum paint on steam radiators?
4. What do we mean by "color"? White light?
5. Should we limit the term "light" to apply only to visible radiation? What about ultraviolet or infrared light?
6. Do all human eyes respond the same to light? Are eyes good instruments for measuring light intensity? Frequency?
7. What range of wave lengths normally correspond to visible radiation? How can the frequencies corresponding to the limits of this range be calculated?
8. What happens to the color of a hot body as its temperature is raised?
9. How do the sun, about 6000°C, carbon arcs, about 4000°C, and tungsten filament lamps, about 2500°C, compare as to the emission of ultraviolet, visible, and infrared radiation? How would the ***luminous efficiencies*** of the latter two compare?
10. How are stellar temperatures determined?
11. How much more power is radiated by a star with a surface temperature of 11,000°C than by the sun (6000°C) if the two are assumed to be the same size?
12. For what reason did Max Planck introduce the quantum theory of light?
13. In what way did the characteristic frequencies emitted by atoms suggest a definite structure to the atom?
14. How may spectrographs be used to study infrared and ultraviolet parts of spectra?
15. What is a Fraunhofer grating? How can it be used to study spectra?
16. How did Nils Bohr make use of the quantum hypothesis to explain characteristic frequencies emitted by "excited" atoms?
17. What was the significance of the famous experiment of Davisson and Germer?
18. What has been the nature of recent modifications of the quantum theory of the atom?
19. What is the basis for Heisenberg's ***uncertainty principle?***

CHAPTER XIX

X RAYS

Late in 1895, Wilhelm Konrad Roentgen, like many other physicists of that time, was investigating electric discharges in highly evacuated tubes. Roentgen was startled to see a near-by barium-platinum compound fluoresce brilliantly when the vacuum



(*Dr. Ross Golden.*)

Fig. 447. X-ray photograph showing a metal pin used as internal splint for fracture of the neck of the femur. The fracture has healed with firm bony union and is not visible in these roentgenograms. (a) Anteroposterior view; (b) vertical view.

in his tube was made so good that a greenish glow was produced on the glass. The effect occurred even though the tube was covered with black paper. Searching for the cause of the fluorescence, he discovered that coming from the anode of his tube was some strange new penetrating radiation which would produce fluorescence in

some compounds through a considerable thickness of material. Even the shadow of the bones of his hand was clearly visible when his hand was placed between the tube and a fluorescent screen. Some years later, when asked by a visiting scientist, "What did

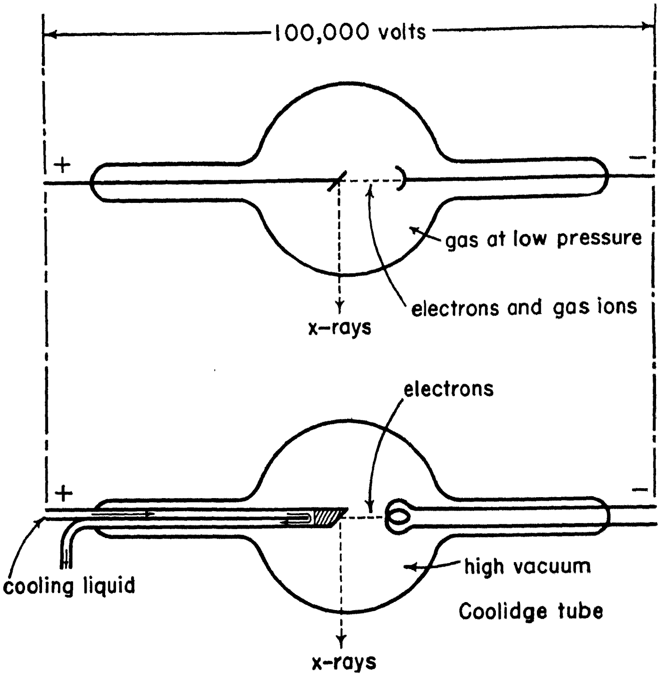
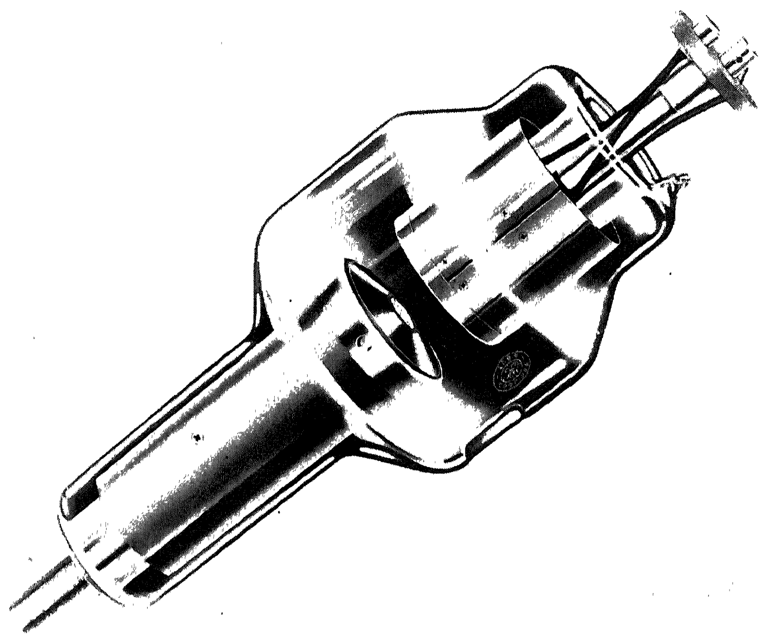


Fig. 448. Gaseous-discharge type and Coolidge type of X-ray tubes. In the earliest X-ray tubes there was a low-pressure gaseous discharge in which the cathode rays struck the metal anode, producing X rays.

In Coolidge's improved tube a filament is used as the electron source so that the tube can be evacuated highly. The anode may be liquid-cooled to dissipate heat from the impinging electrons.

you think then?" Roentgen replied, "I did not think, I experimented!" Not entirely certain of the nature of the new radiation, he called it "X rays." He found soon that X rays would affect photographic plates and that shadow pictures could readily be taken of objects interposed between the source and a plate. Undoubtedly, Sir William Crookes and many others had produced X rays long before, but it remained for Roentgen to recognize that something new was happening and to study the effect systematically.

Roentgen's discovery was heralded widely, and many experimenters began to investigate further. The ability of X rays to ionize air and discharge electroscopes was soon discovered. X rays were found to pass easily through materials of low atomic weight, but

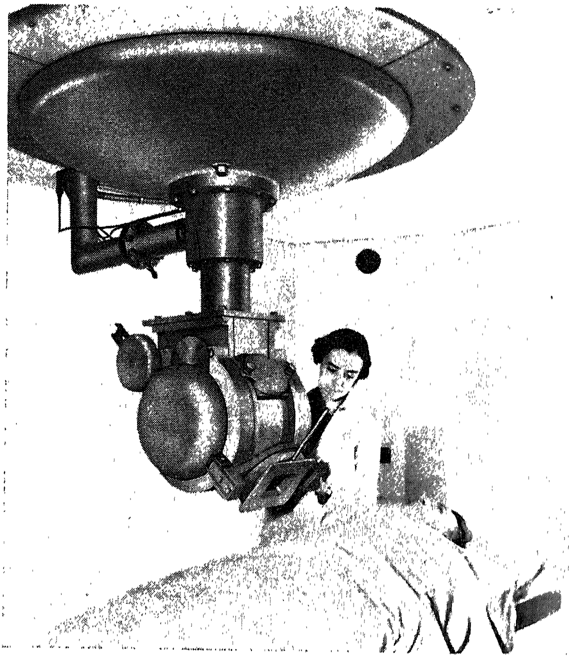


(*General Electric Company.*)

Fig. 449. Modern rotating target X-ray tube. This tube gives much higher X-ray output than can be obtained from a conventional tube. The target is rotated in vacuum at 3,500 revolutions per minute. High-intensity electron beams can be used without damage to the target such as results when the electron beam strikes one region continuously.

to be much more readily absorbed in materials of high atomic weight. Four days after news of the discovery reached America, X rays were used to locate a bullet in a patient's leg, and within a year this radiation was adopted in many parts of the world for medical examinations, particularly of bone fractures. For pure and applied science a great tool had been found, and for humanity there was the means of saving the lives of millions. This was at the sacrifice of some of the early X-ray workers who were either maimed or fatally injured before the dangerous character of the radiation was fully realized.

Producing X Rays. Experiments soon showed that X rays are produced when high-speed cathode rays, or electrons, strike a metal anode, or "target." Early X-ray tubes contained a cathode of any convenient metal and an anode of platinum or of some other



(*General Electric Company.*)

Fig. 450. Treatment room for 1 million volt X-ray installation at Memorial Hospital in New York City.

metal with a high melting point. These parts were enclosed in an evacuated tube which still had a slight trace of residual gas so that a discharge could take place when a high voltage, say 50,000 to 100,000 volts, was placed across the tube. The output of such a tube was rather unstable since the amount of residual gas could not be well controlled. In 1913, W. D. Coolidge of the research staff of the General Electric Company introduced a hot filament as an electron-emitting cathode, and evacuated the tube highly to eliminate the effects of residual gas. Tungsten, often water cooled, became the usual target material. This X-ray tube (Fig. 448) proved much more satisfactory than the older type.

X rays were found to increase in penetrating power with increase in the voltage used to accelerate the electrons on their way

to the target. Therefore, progressively higher voltages have been applied to X-ray tubes as techniques have been developed to produce high voltages and tubes capable of withstanding them.

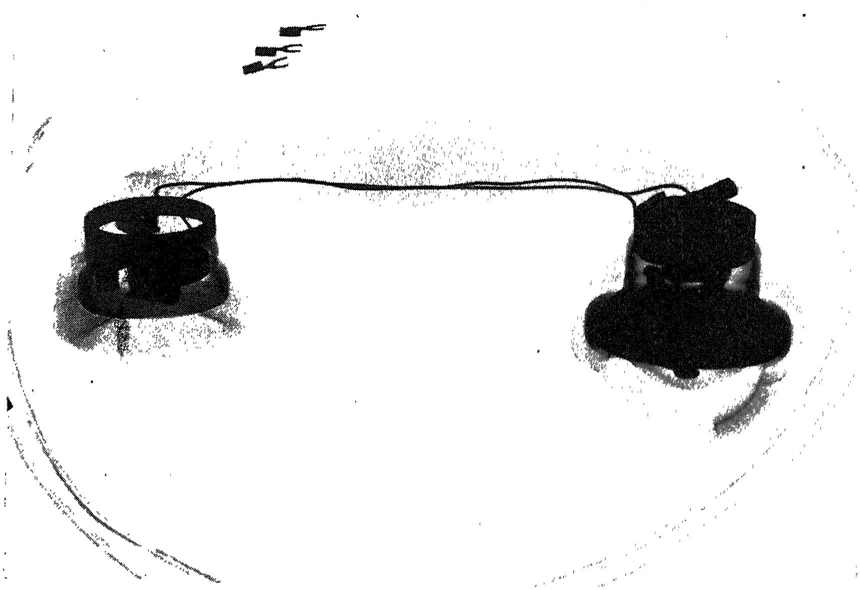
Today the X-ray unit that your dentist uses probably operates

(*General Electric Company.*)

Fig. 451. Several sections of 1,400,000 volt X-ray tube at National Bureau of Standards, Washington, D. C. Operation of supervoltage tubes without breakdown is made possible by constructing them in many sections with comparatively low voltage across each section.

at 50,000 to 100,000 volts, and in many special units in hospitals and laboratories where more penetration is desired the potential difference may be 250,000 volts. A number of new installations function at 1,000,000 volts, and still higher voltage equipment is contemplated even though the X-ray penetrating power does not increase so markedly as voltages are pushed above a million.

More and more X-ray testing is being utilized in industry—to inspect welds for hidden flaws, large castings for blowholes, steel armor plate for nonuniformity, etc. Even shoe stores put X rays to such mundane use as to check the fitting of shoes.

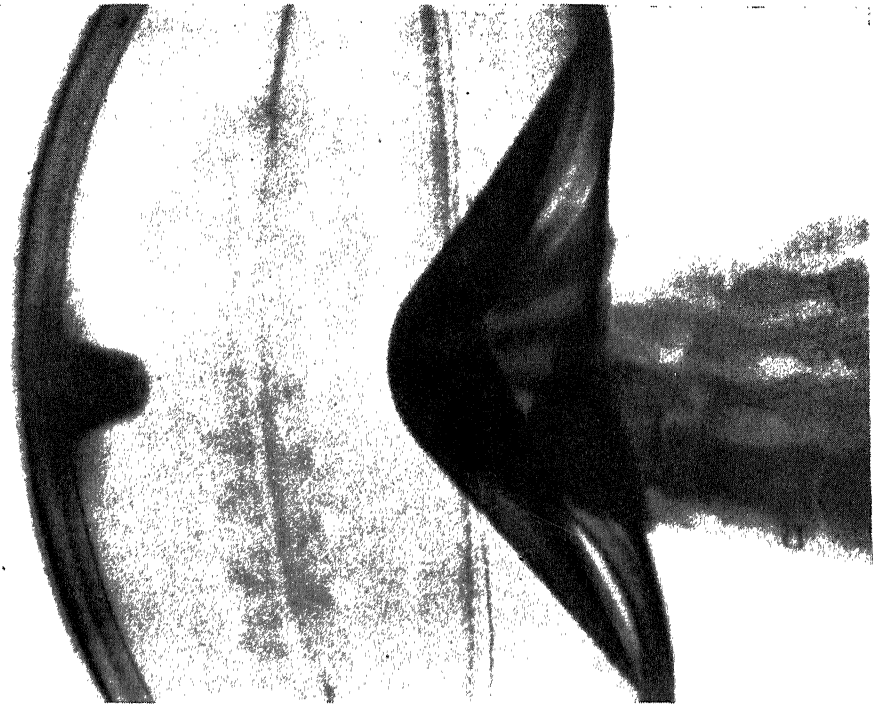


(*Bell Telephone Laboratories.*)

Fig. 452. X-ray photograph of telephone handset. X rays frequently prove convenient for inspection of assembled apparatus or packed goods. Compare with Fig. 402.

Nature of X Rays. For a long time there was much controversy about the nature of X rays. Most physicists believed them to be very short waves, but for a long time no definite proof was found — no way could be discovered to refract them or to cause interference.

Finally, in 1912, Professor von Laue in Berlin had the brilliant idea that, if X rays are waves of shorter length than visible light, atoms in a crystal might be spaced about right so that crystal planes could serve as "gratings" for this radiation. Experiments were quickly carried out at his suggestion by interposing a crystal between an X-ray tube and a photographic plate. Immediately a number of "spots" were observed on the plate. By trying various crystals, it was found that the positions of these spots depend on the arrangement of atoms in the crystal. Calculations showed that X rays did have wave lengths of the same order as interatomic spacing in crystals, that is, in the region of about 2×10^{-8} cm — more than 1,000 times shorter than waves of the visible spectrum. X rays are electromagnetic waves that travel with the speed of light; they differ from visible radiation only in frequency (and, of course, wave length).

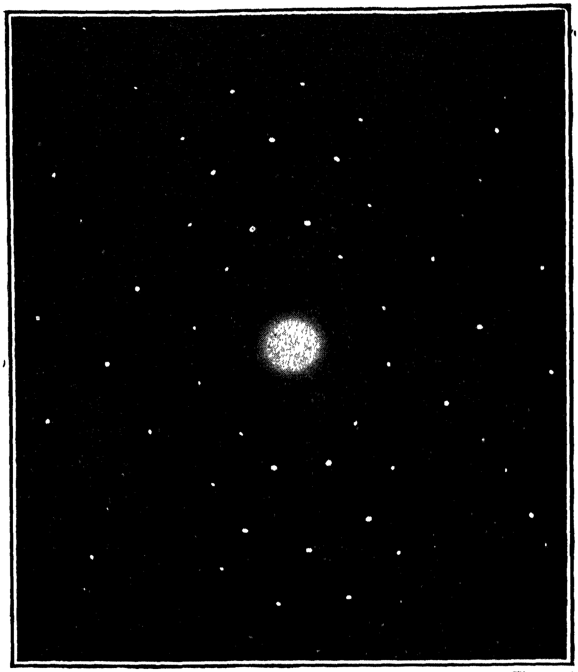


(*Westinghouse Electric and Manufacturing Company.*)

Fig. 453. Ultrahigh-speed X-ray photograph. The football was kicked sideways to show details of both the football and the bones in the kicker's foot. The tube used permits exposures of one-millionth of a second.

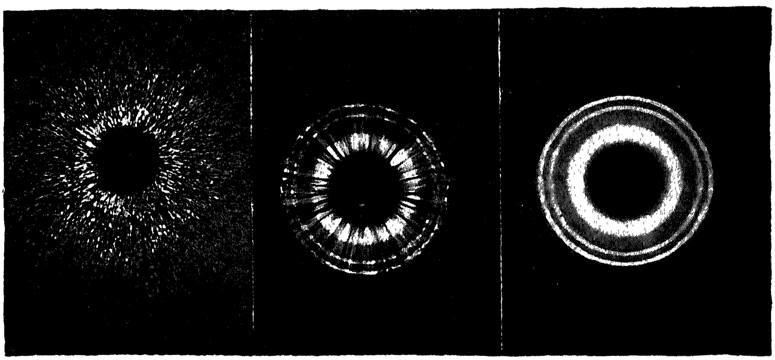
The photoelectric effect gives us a clue as to why X rays produce ionization. Since X rays are of short wave length, their quantum energy is very high, so they are able to "pull" electrons out of virtually any material. Of course, they can produce photoelectrons far more easily than the lower energy ultraviolet and visible quanta which are at best barely able to overcome the forces which hold the more weakly bound electrons to their parent atoms.

"Seeing" the Structure of Matter. Crystallographers, metallurgists, physicists, and chemists saw immediately that the "Laue spot" photographs provided an excellent method for studying the structure of matter. The arrangement of the spots on a plate reveals clearly to the experienced eye the orderly arrangement of atoms in materials. The technique of X-ray analysis has been much refined, until it now provides one of the main sources of our knowledge of structure of minerals, of alloys, of chemical compounds, and even of biological materials.



(*George L. Clark, Applied X-rays.*)

Fig. 454. "Laue spot" X-ray pattern produced by an iron crystal.



(a) (b) (c)

(*George L. Clark, Applied X-rays.*)

Fig. 455. X-ray diffraction patterns show changes in structure with steps in rolling of low-carbon sheet steel. (a) Hot-rolled strip. (b) One pass through mill, 7 per cent reduction in thickness. (c) Nine passes through mill, 47 per cent reduction in thickness. See electron diffraction patterns, Fig. 443.

X-ray Spectroscopy. About 1910, Sir William Bragg made use of a crystal as a "reflection grating" for X rays. This so-called *X-ray spectrometer* was something like the arrangement of Fig. 456. The only X rays reflected strongly at any given angle were those of

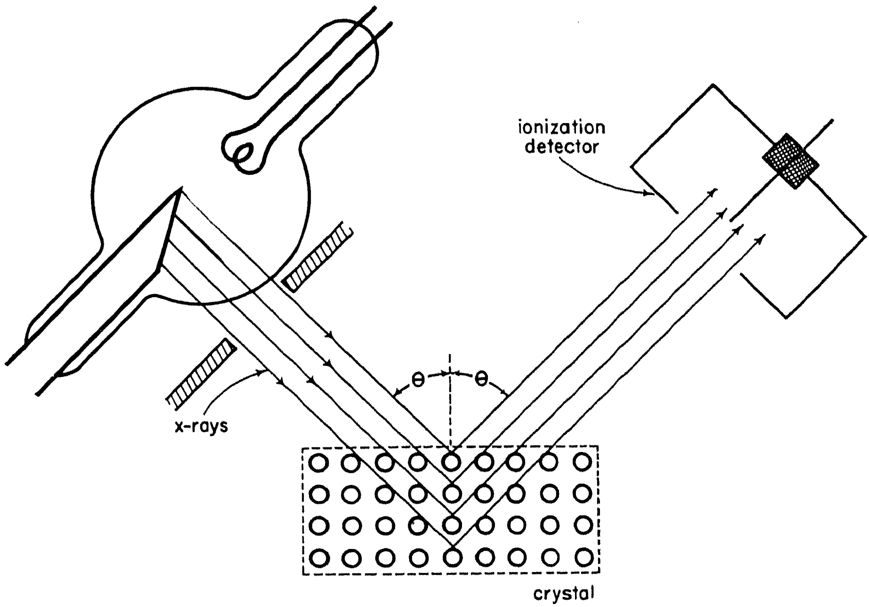
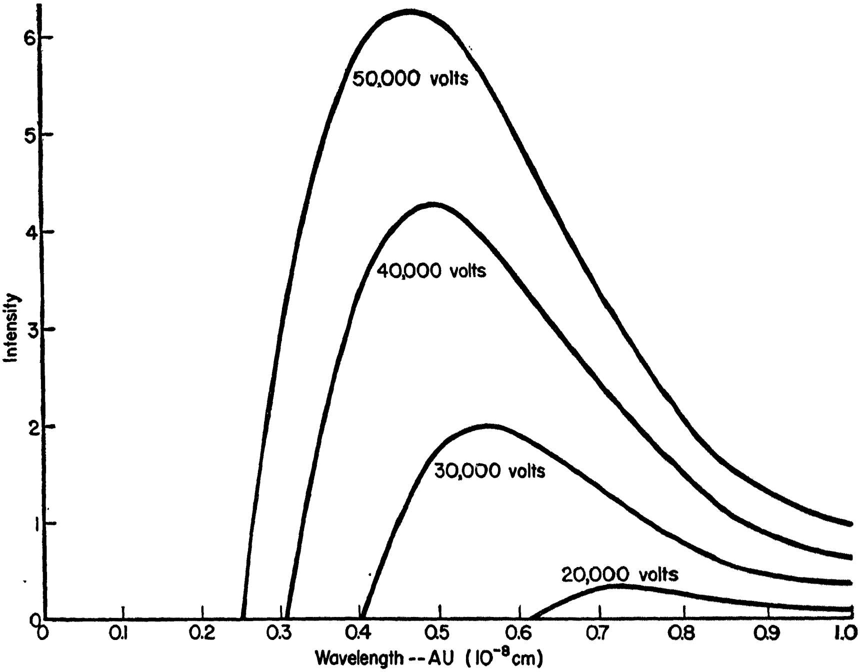


Fig. 456. Bragg's crystal spectrometer for X rays. By changing the angle θ, X rays of different wave lengths are selectively reflected from the crystal planes and detected in an ionization chamber. Once calibrated, the "spectrum" of the X rays from any source can be obtained. Actually, θ should be nearer 90°. The atoms in the crystal are of course greatly exaggerated and in practice the X-ray beam is made much narrower by slits.

the particular wave length for which there was constructive interference. This wave length depends upon the angle and the distance between planes of the crystal. By rotating the crystal and thus reflecting rays of different wave lengths, the spectrum of the incident X rays could be determined in much the same way that a prism spectrometer or a grating spectrometer is used for spectra in the visible, ultraviolet, and infrared regions. Usually the X rays are detected by the ionization they produce in a special chamber called an *ionization chamber.*

X-ray spectra were found to be of two different types somewhat like visible spectra: continuous spectra, and line spectra. Their study has led us to most of our knowledge about the innermost electron structure of all but the lighter atoms.

X-ray Continuous Spectra. Typical X-ray continuous spectra (disregarding the lines which are frequently superimposed) are reproduced in Fig. 457. They look somewhat like the continuous spectra emitted by "black bodies" at high temperatures, but ex-



(*After C. T. Ulrey.*)

Fig. 457. Continuous spectra of X rays from a tungsten target. As the energy of the impinging electrons is increased (i.e., as the tube voltage is increased) the spectrum becomes more and more intense and extends to shorter wave lengths (i.e., higher frequency and greater quantum energy).

hibit sharper short-wave-length, or high-frequency, limits. As the voltage across the X-ray tube is increased, the electrons impinge on the target with greater energy, so the "peak" and the high-frequency (short-wave-length) limit of the spectrum produced move toward a higher frequency value. This is just what one might expect from an increase in maximum quantum energy, which means an increase in maximum frequency or a decrease in minimum wave length. The same continuous spectrum is observed for all target elements. In fact, the highest X-ray frequency which can be produced by an electron of a given energy is given by Planck's relation.

$$\text{Electron energy} = h(\text{frequency limit})$$

that is, to give the limiting frequency value, all the energy of the electron must be converted into a quantum of radiant energy. This is indeed just the reverse of the photoelectric effect, where a quantum of light energy falling on matter is converted into a photo-

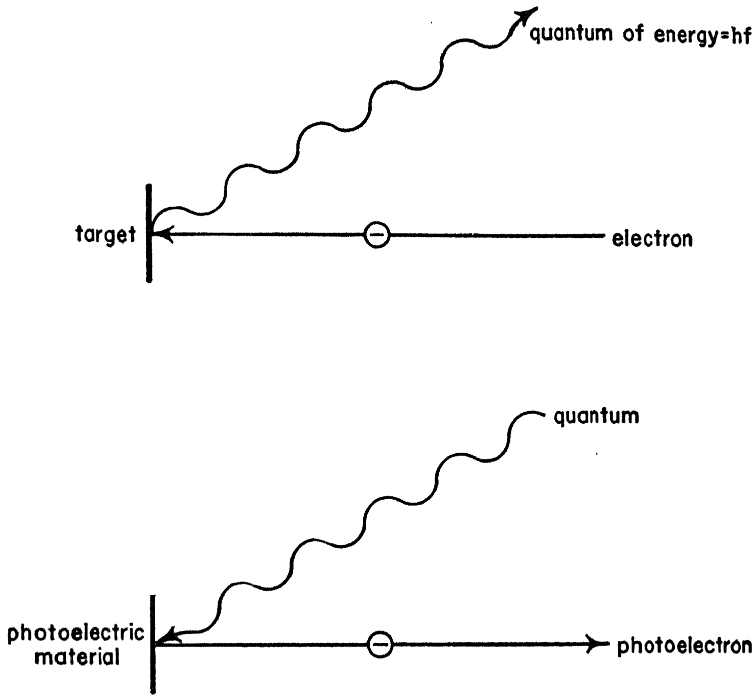
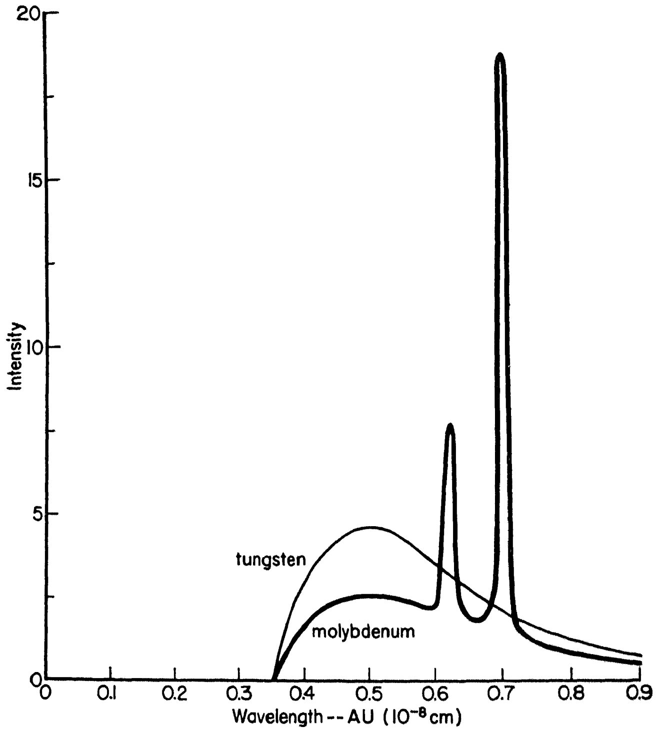


Fig. 458. X-ray emission is the reverse of the photoelectric effect. In X-ray production an energetic electron striking the target surface sends out an X-ray photon. Photoelectric emission is the reverse, the photon releases an electron when it is absorbed by some atom in the photoelectric surface.

electron (which has a little less energy than the quantum because of the energy required to pull an electron out of the material).

X-ray Line Spectra. If the energy of the impinging electron is high enough, all X-ray continuous spectra actually have superposed on them "lines" which are characteristic of the element composing the target. Investigation has revealed that these lines are just of the typical frequencies expected, according to the Bohr theory, from the inner electron orbits of the atoms of the target material. The innermost, second, and third electron orbits are

usually designated by K, L, and M, respectively. Moseley showed that all X-ray spectra have essentially the same arrangement and that if elements of progressively higher atomic number are used as targets, the frequencies of the characteristic K, L, and M lines



(*After C. T. Ulrey.*)

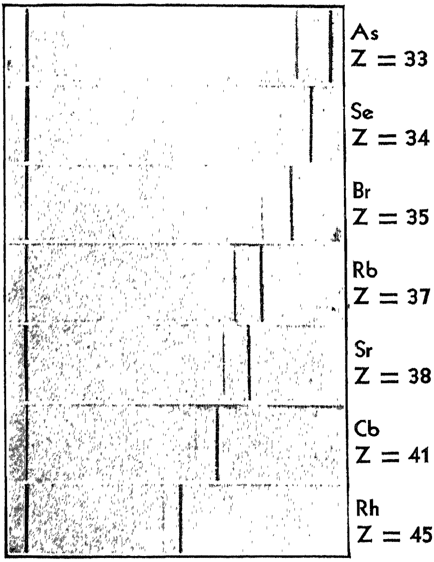
Fig. 459. X-ray "lines" superposed on the continuous spectrum from a molybdenum target. The continuous tungsten spectrum at the same voltage, 35,000 volts, is shown for comparison.

Frequencies of the two molybdenum "lines" are emitted when, after being excited by electron bombardment, the first and second electrons, respectively, return to their normal positions in the inner shell of the atom (the "K shell").

(Fig. 460) become progressively higher (or the wave lengths shorter). This is just as we should predict, for with increase in atomic number the inner electrons are bound more tightly because of the increased nuclear charge, so more energy is required to "excite" them. This greater excitation energy is emitted as quanta of increased energy and frequency.

To produce the K series of lines from the heaviest element, uranium (wave lengths about 10^{-9} cm), electrons accelerated by

about 100,000 volts are required. On the other hand, only a few volts are needed to produce the K series of the lightest element, hydrogen (wave lengths about 10^{-5} cm). In both cases, however, the method of production is the same; that is, if an electron is



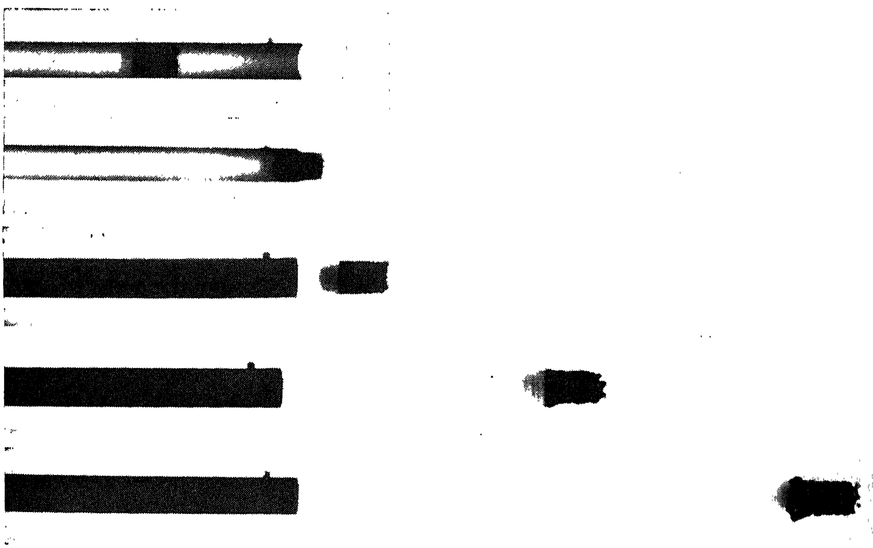
(*George L. Clark, Applied X-rays.*)

Fig. 460. K-series spectral lines as photographed by Moseley for several near-by elements. This illustrates the continual increase in frequency of these lines with increasing atomic number (Z).

knocked out of its orbit by an impact, then, on returning to the orbit, the excess energy which it had in the "excited" state is radiated as a quantum. Thus X-ray spectroscopy is but an extension of ordinary spectroscopy except that the wave lengths are shorter and the frequencies higher.

X-ray spectra have revealed to us the details of the inner electron orbits of the atoms and strengthened the foundation for the fundamental concepts of the Bohr theory of the atom. They have greatly extended our knowledge of the spectrum of electromagnetic waves, and, again, we see great similarities between the radio and visible and very short X-ray waves, all of which travel with the same speed, 186,000 miles per second, and differ only in wave length or frequency.

The fruits of Roentgen's discovery have truly given new eyes which see even through atoms, powerful tools for scientific research, and innumerable practical applications for medicine and industry.



(*Westinghouse Electric and Manufacturing Company.*)

Fig. 461. Ultrahigh-speed X-ray photographs of flight of a shotgun charge from the barrel of a shotgun. Shot does not begin to scatter until it has cleared the muzzle by about a foot.

FOR STUDY AND READING

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SUMMARY

In 1895, Roentgen discovered a penetrating radiation from well-evacuated discharge tubes. These X rays affect photographic plates and penetrate elements more readily the lower the atomic weight, making possible X-ray photography.

X rays are produced whenever electrons of sufficient speed strike matter. In 1913, Coolidge developed the modern highly evacuated X-ray tube with a hot electron-emitting filament as cathode, and with an anode usually of tungsten. The penetrating power increases with tube voltage to above a million volts.

X rays were identified as waves by Laue interference patterns produced when crystals were used as "gratings." They show all the characteristics of electromagnetic radiation with much shorter wave lengths than light. X rays can ionize by photoelectric action. From interference patterns of X rays of known wave length the structure of crystals can be studied.

Bragg constructed a spectrometer for X rays, using the fact that the wave length of X rays strongly reflected from a crystal depends simply on the angle at which they strike the crystal. With it both continuous and line X-ray spectra were found. The high-frequency limit of the continuous spectrum is given by

$$\text{Energy of electrons producing the X rays} = h(\text{frequency limit})$$

The continuous spectrum is the same for all target materials.

The line spectra are of frequencies expected according to the Bohr theory from the inner electron orbits of the target atoms. With increase in atomic number, the characteristic X-ray quantum energies increase, ranging from a few volts for hydrogen (wave lengths of about 10^{-5} cm) to about 100,000 volts for uranium (wave lengths of about 10^{-9} cm).

QUESTIONS

1. What was the nature of the investigations which led to Roentgen's discovery of X rays in 1895? Would you term this discovery entirely accidental?
2. What characteristics of X rays make possible their use for medical diagnosis, industrial inspection, etc.?
3. How does the Coolidge X-ray tube differ from the early gas-filled type?
4. What experiment settled the old controversy as to the nature of X rays?
5. Why should X-ray absorption, in general, increase with the density of the absorbing material? Is this related to the number of electrons per unit volume of the material?
6. How did von Laue's suggestion that crystals be used as interference gratings for X rays lead to an important method of investigating crystal structure?
7. How did Bragg obtain X-ray spectra?
8. When materials are bombarded with high-speed electrons, why should we expect electromagnetic radiation to be emitted?
9. Is it fortuitous that the maximum frequency of a continuous X-ray spectrum is determined by the energy of the bombarding electrons according to the quantum relation: Energy $= h \times$ frequency?
10. How do X-ray line spectra originate? What can they reveal about the structure of the atom?
11. About what is the range of wave length of X rays?
12. Is the following statement (page 576) consistent? Electrons accelerated by about 100,000 volts are required to produce the K lines of uranium (wave lengths about 10^{-9} cm), but only a few volts are needed to produce the K series of hydrogen (wave lengths about 10^{-5} cm).
13. What are some applications of X rays in medicine and industry?

CHAPTER XX

THE ATOM'S NUCLEUS

RADIOACTIVITY

Discovery of Radioactivity. In the period between 1895 and 1900, just after brilliant researches had led to the discoveries of the electron and X rays, many investigators were studying the production of fluorescence in minerals by X rays and ordinary light.

In Paris in the year 1896, Henri Becquerel was particularly interested in the fluorescence of uranium compounds when, almost by accident, he discovered a strange phenomenon which proved to have important consequences. He intended to expose uranium compounds to sunlight, and then place them next to photographic plates to detect the fluorescence. However, it was bad weather, and, as the sun did not shine, the plates and the uranium minerals were left together in a drawer for several days. He developed the plates anyhow and was surprised to find them darkened even though they had been well wrapped. Here was something new, and Becquerel lost no time in investigating it. These radiations emitted by uranium compounds were able to affect a photographic plate through many thicknesses of paper, and even through pieces of brass and lead. He soon found that the uranium metal itself, and not the compound, was responsible for this phenomenon. He sought further and discovered that the new radiations ionized the air and quickly discharged near-by electroscopes.

Other researchers hastened to study the new effect which became known as *radioactivity*. Pierre Curie and his wife Marie found that thorium behaved similarly, and in 1898, by chemical separation of pitchblende ores, they isolated two new radioactive elements, both many times more active than uranium. These they named *polonium* (in honor of Madame Curie's native land, Poland) and *radium*.

As in any new field, many conflicting results were reported at first, but gradually the essential facts concerning radioactivity be-

came clearer. A rapidly increasing group of workers discovered that a large number of radioactive elements exist, all of them of high atomic weight and beyond lead (atomic number 82) in the periodic table. Evidence mounted to show that most of the radioactive elements are produced in turn from other radioactive elements, and, in fact, that three separate series of radioactive elements exist, the ***uranium series***, the ***thorium series***, and the ***actinium series***. In each series one element is transformed into the next, until finally stable lead is reached. No type of physical or chemical treatment could be found which affected in the least the radioactive processes, and it was rightly concluded that radioactivity must be an internal property of the atom itself, or, as we know today, of the central core, or ***nucleus***.

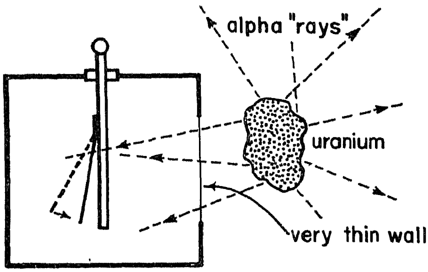


Fig. 462. Becquerel discovered that from uranium there is radiation which can discharge an electroscope.

Great differences in the character and amount of activity from the various elements were observed, and three major types of radiation were soon recognized. These radiations were originally called ***alpha, beta,*** and ***gamma rays,*** in order of increasing penetration, and today we still use the same names. In time their properties were determined and their nature identified.

An outstanding investigator of radioactive radiations was the late Lord Rutherford, 1871–1937, who went to Cambridge University from New Zealand, and then to McGill University in Canada where much of his early work was done. Later he returned to England and eventually became director of the Cavendish Laboratory at Cambridge, where, under his leadership, there was a long series of brilliant researches on radiation from radioactive substances.

Madame Curie, who carried on at the Institut du Radium in Paris after her husband's death, Professor Otto Hahn in Berlin, and numerous others contributed notably to this stage of the work on radioactivity.

Alpha Rays. Even with comparatively crude electroscopes, it was soon found that there exists a type of powerfully ionizing radiation capable of penetrating only a few centimeters of air, or perhaps a few thousandths of a centimeter of aluminum. Rutherford

was the first to show conclusively that this alpha radiation is really a stream of high-speed helium ions shot out by disintegrating radioactive atoms. He managed to pass enough of the alpha rays through

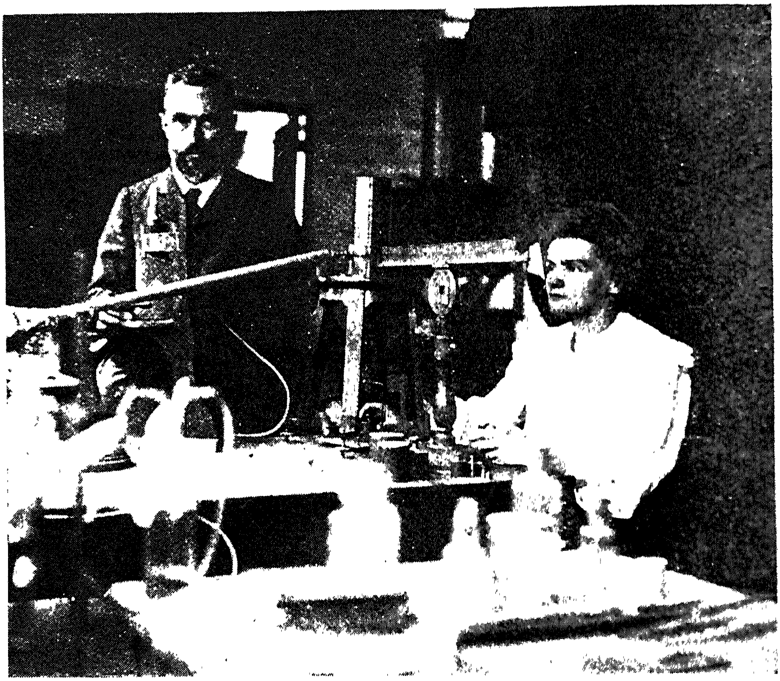


Fig. 463. Pierre and Marie Curie in their laboratory.

a thin foil into a discharge tube so that the characteristic lines of helium were observed with a spectroscope.

By applying the same methods of electric and magnetic deflection that Thomson used for the study of electrons, Rutherford learned that these alpha rays, or *alpha particles* as we now call them, are really "stripped" helium atoms which have lost their outer two negative electrons and, therefore, have a positive charge of two elementary units. These particles are shot out from radioactive nuclei at speeds ranging up to 15,000 miles per second. As they go through air, they rip electrons off the air molecules, and thereby expend their energy while producing many ions along their paths. The distance they go in air is called their *range*. While this range is fairly constant for alpha particles from any given element, it differs considerably among those emitted from the various

elements; alpha particle ranges vary from about 3 cm from uranium I, to 12 cm from thorium C′.

Beta Rays. Beta rays, constituting the type of radiation with intermediate penetration, were found by the familiar method of

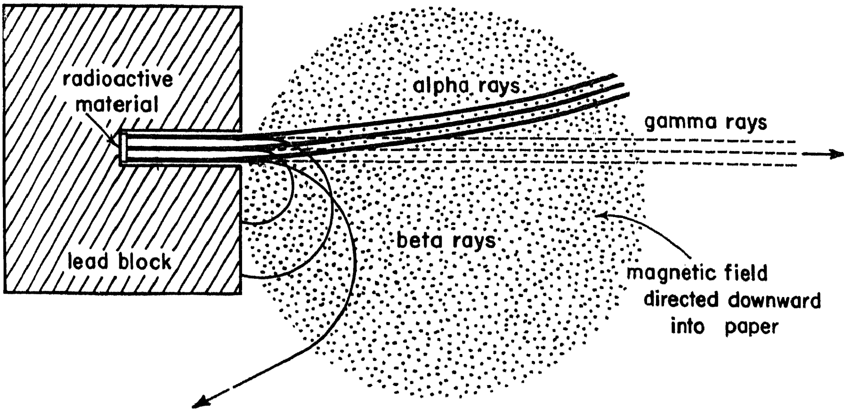


Fig. 464. Influence of a magnetic field upon radioactive radiations. Alpha rays are deflected slightly, like a current of positively charged particles. Beta rays are strongly deflected, like a current of negatively charged particles. Gamma rays are unaffected by the magnetic field.

electrical and magnetic deflection to be very high-speed *electrons*. Most of these electrons travel much faster than the highest speed cathode rays normally produced in the laboratory, and some reach nearly the velocity of light! Beta particles can traverse much more matter than do alpha particles, often through several meters of air, or one-tenth centimeter of aluminum. The ionization along their paths is about 100 times less than for alpha particles.

Gamma Rays. The gamma rays are the most penetrating of all nuclear radiations, usually much more penetrating than ordinary X rays. A centimeter of lead is required to absorb half of the gamma radiation from some radioactive elements. Because this radiation is unaffected by electric and magnetic fields, it was quite natural to think of it as belonging to the same class with X rays or light waves, that is, electromagnetic radiation, but with even higher frequencies than X rays. Gamma-ray frequencies actually range up to about 10^{20} vibrations/sec, and the corresponding wave lengths extend down to 3×10^{-10} cm.

Alpha, Beta, and Gamma Rays in a Magnetic Field. In a magnetic field like the one represented in Fig. 464, the paths of the alpha particles, or helium nuclei, are turned very slightly to the left.

The gamma rays are totally unaffected. The beta rays, or negative electrons, are deflected to the right so strongly that their paths are curled into complete circles.

Detecting Single Particles. Much of the progress in the study of

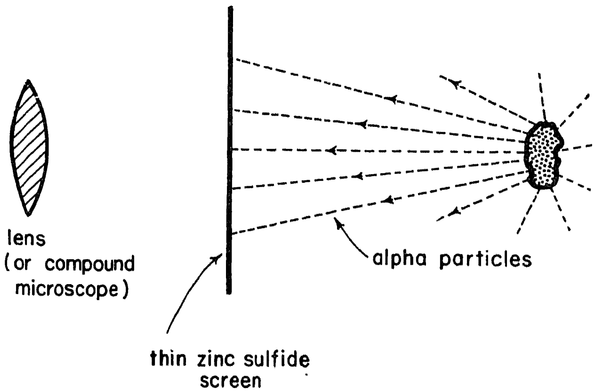


Fig. 465. "Scintillation screen" for detecting alpha particles. Each alpha particle that strikes the zinc sulfide screen produces a tiny fluorescent lightflash, which can be seen with the aid of a magnifying glass.

radioactivity and atomic nuclei has been made possible by the development of devices so sensitive that they can detect single atoms, single electrons, or single quanta. Many of the original experiments in this field were made with comparatively insensitive instruments like electroscopes (page 275) to detect ionization. Such instruments respond appreciably only to the superimposed ionization effects of many alpha or beta particles.

Scintillations. Alpha or beta particles, when striking materials such as zinc sulfide (ZnS), cause these materials to fluoresce. During the study of this fluorescence, it was soon discovered that tiny flashes of light may be seen when alpha particles are allowed to fall on a thin zinc sulfide screen if the screen is viewed under a microscope *in a very dark room* with "dark-adapted" eyes. Each "scintillation" is due to the disruption of part of a zinc sulfide crystal by the impact of a single alpha particle. Trained observers can count the individual flashes, but the latter are so faint and so near the limit of vision that accurate observation is difficult. In fact, one might well marvel at the amount of good work done with this type of detector.

Ionizing Particle Counters. Rutherford, Geiger, and Mueller were principally responsible for the initial development of a simple

and ingenious method of detecting single particles by electrical means. Figure 466 shows a modified form of such a device. Two electrodes, one a cylinder, the other a fine wire along the axis of the cylinder, are both enclosed in a glass envelope which has a very

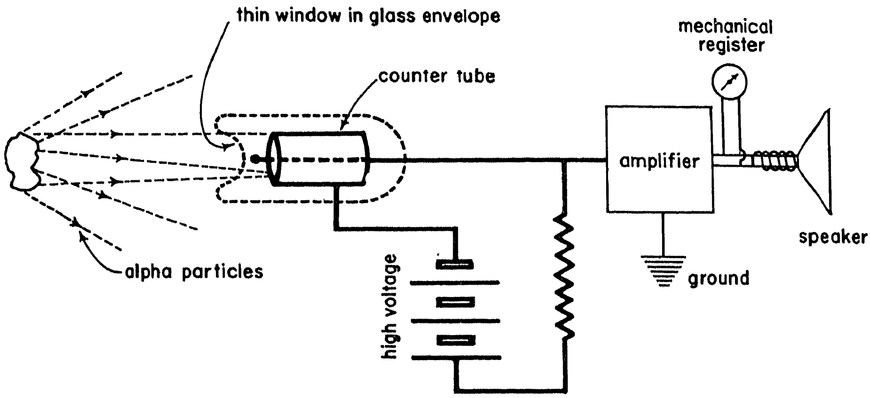


Fig. 466. Counter to detect single ionizing particles. An alpha particle (or other ionizing particle) entering the counter causes a small electrical discharge to occur between the metal cylinder and wire. The resulting electrical pulse, when amplified, can operate a mechanical register and produce a click in a loud speaker.

thin film of glass for a "window." There is gas in the tube at a pressure of perhaps one-tenth atmosphere. A high voltage is applied between the electrodes—so high that the gas is just ready to "break down" and produce a discharge if only some free electric charges are present to start cumulative ionization by impact (see page 447). Now suppose that a radioactive source emitting alpha particles is brought near. When an alpha particle goes through the thin window into the *counter,* it rips up the gas molecules, producing some free ions which start a tiny cumulative discharge. This discharge is stopped before it builds up very far, because the voltage supply circuit is arranged so that the potential difference is temporarily reduced during the discharge. The tiny electric pulse "triggered" off by the single alpha particle can then be amplified and made to produce a "click" in a loudspeaker, to operate a registering instrument, or, in fact, to start almost any desired electrical apparatus.

A beta ray (or electron) also triggers off such a counting device, and a gamma ray can do likewise because a gamma-ray quantum has enough energy to liberate a photoelectron from any

material. In fact, by adjustment of wall thickness, internal construction, and operating conditions, counting tubes can be made preferentially sensitive to the various types of radioactive radiation. This discriminating ability adds greatly to the value of these instruments.

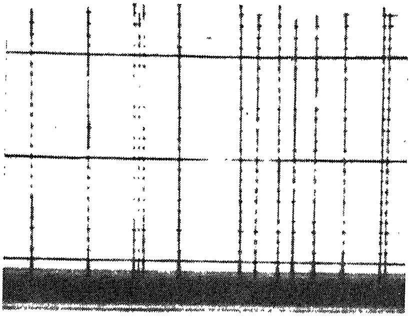


Fig. 467. Oscillograph records of ionization produced by alpha particles of uniform energy from polonium.

Figure 467 shows a photographic record of oscillograph deflections from alpha particles detected by a particle counter. Each "spike" on the record represents the arrival of a single particle. Note that there is no regularity, for the disintegration of a radioactive atom is a perfect example of pure chance. Great care must be exercised, and statistical methods must be used, in evaluating results which involve the rate of arrival of these particles (see page 373).

So sensitive can counters be made, particularly if the cylinders are coated with photoelectrically sensitive material, that one light quantum from a match hundreds of feet away can be detected by the liberation of a single photoelectron inside the counter.

Actually, the particle counter is the most sensitive instrument devised by man, millions of times more sensitive than most laboratory devices, for it detects the ultimate particles of matter, and a single free electron is enough to trigger it off. This sensitive tool has been an invaluable aid in extending investigations to the world of infinitesimals.

The Cloud Chamber. The ***cloud chamber,*** though less sensitive than the counter, gives a still more concrete picture of the behavior of subatomic particles. The fact that fine dust or smoke particles serve as "nuclei" about which water vapor condenses as fog has been known for a long time, but, in 1910, C. T. R. Wilson first applied this sort of effect to the detection of radioactive radiations.

A cloud chamber, as Wilson's apparatus was called, may be constructed as in Fig. 468. The bottom of the chamber is a gastight piston. There is an arrangement for suddenly lowering the piston (often by compressed air) so that gas which fills the chamber can

be expanded suddenly. After an expansion, the piston is returned to its normal (upper) position.

Within the chamber is a pad soaked with any of a number of liquids, say water. Then, in addition to the gas in the chamber,

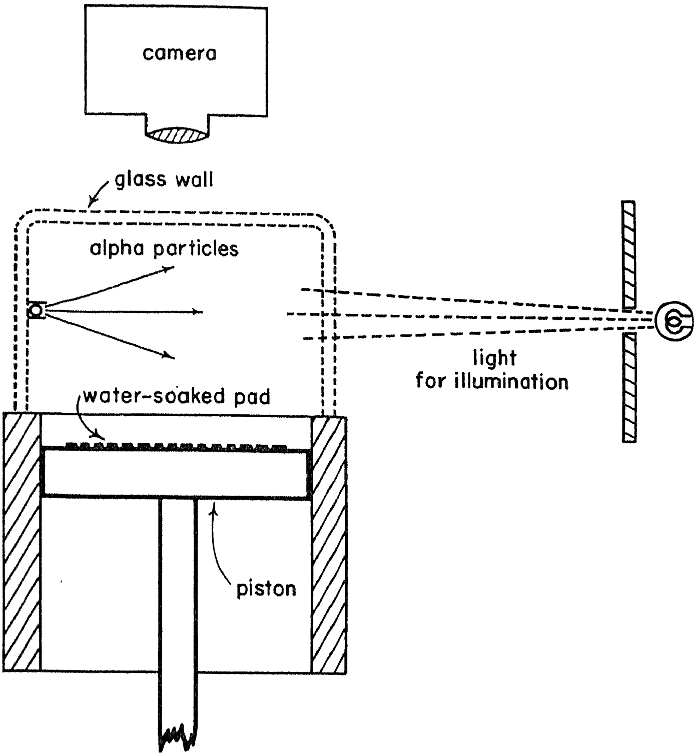
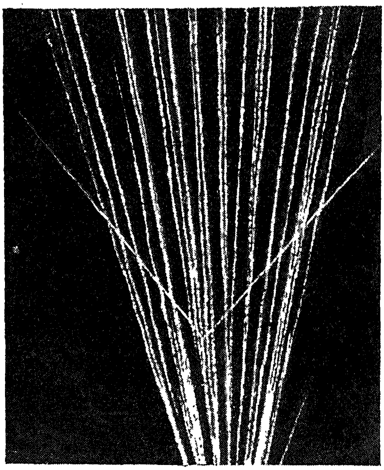


Fig. 468. Cloud chamber. The enclosure above the piston contains air and saturated water vapor. If the piston is suddenly dropped a certain distance, the water vapor becomes supersaturated (the expansion cools the enclosed gases). If the adjustment is correct there will be condensation of the water vapor only if there are ions (or dust particles) on which droplets can form. Under this condition, droplets of water condensed on ions liberated by an alpha particle (or other charged particle) passing through the chamber, leave a visible trace of the path of the particle.

which we take to be air, there will be saturated water vapor (page 391). If the interior of the chamber is suddenly cooled by about 30°C, less vapor is required for saturation and the excess condenses as fine droplets, in other words, as a fog. If, on the other hand, the amount of cooling is somewhat less, the excess vapor will not condense unless there are dust particles, smoke particles, or *ions* to act as nuclei about which the droplets can form. This cooling is

accomplished by suddenly expanding the gas in the chamber (page 393).

Suppose that at the instant an expansion is made, an alpha or beta particle passes through the chamber. Then the ions produced in the gas by the particle serve as nuclei for the formation of droplets, and a track of water droplets marks the course of the particle.



(*Blackett.*)

Fig. 469. Cloud chamber tracks of alpha particles. One particle has been deflected by an impact with a helium nucleus. See Fig. 133, page 198.

Alpha particles ionize heavily and so leave dense tracks in a cloud chamber. Note in Fig. 133 that the alpha-particle tracks all have about the same range (all are from the same radioactive element). In Fig. 469 something has happened to one of these high-speed helium nuclei, for it seems to have been deflected suddenly in its course. The interpretation of this, as we shall see, is that the alpha particle has happened to hit another atomic nucleus, and, therefore, was bounced off at an angle.

Beta rays produce little ionization and so form "thin" cloud tracks. In general, the density of a track in a cloud chamber gives a good clue to the identity of the particle which produced it. Often the cloud chamber is placed in a magnetic field so that the particles detected are forced to travel in circular paths. The faster the particles, the less the tracks are curved. From relations similar to those used by Thomson for cathode rays (see page 452), the speed and, therefore, the kinetic energy of the particles can be determined. The vivid cloud pictures of the behavior of these speeding subatomic particles have made the cloud chamber an exceedingly useful tool for studying radiations from atomic nuclei, as well as other energetic radiations known as cosmic rays (Chap. XXII).

Discovering the Atom's Nucleus. One most important experiment which revealed the structural nature of atoms was performed by Rutherford. In this study, he used the alpha particle as a probe to investigate the interior of the atom itself. Out of his experiments

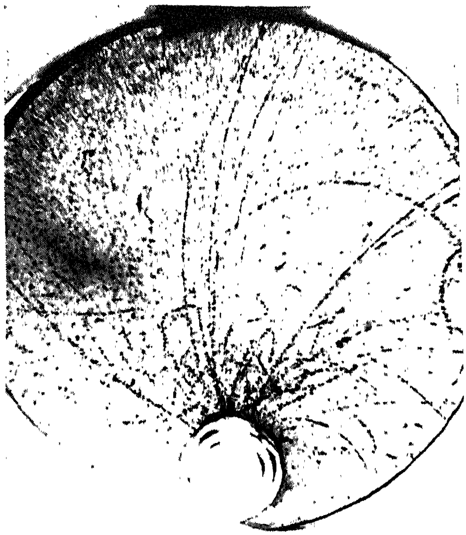


Fig. 470. Beta-ray tracks in a cloud chamber (negative print). There is a uniform magnetic field directed downward through the chamber (into the paper), which makes the beta particles follow circular paths. The paths with slight curvature are for particles of higher speed than those which followed the strongly curved tracks.

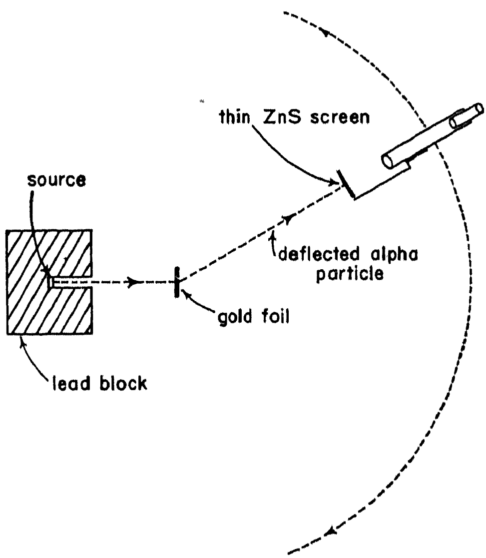


Fig. 471. Rutherford studied the scattering of alpha particles by atomic nuclei. The observed angular distribution of alpha particles scattered by impacts with gold atoms in the foil led him to the concept of the nuclear atom.

grew our present ideas of the atom as something, crudely speaking, like a "miniature solar system." We have already made use of the modern picture of the Rutherford nuclear atom, but now we shall look more closely at the experiments which led to it.

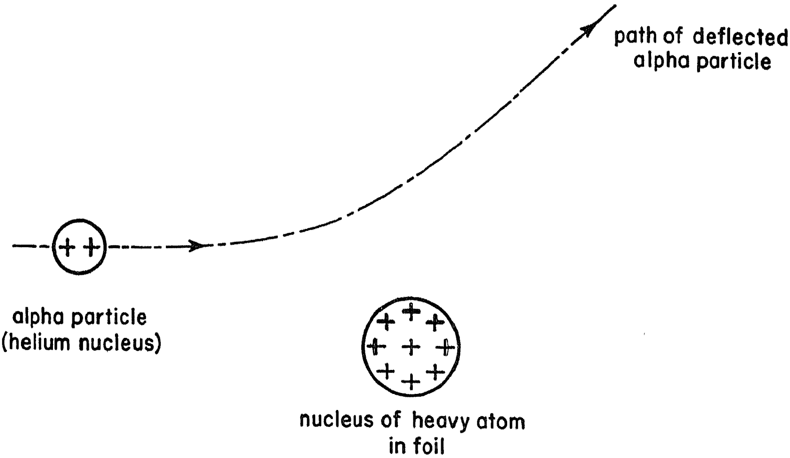


Fig. 472. An alpha particle passing close to a nucleus is deflected as a result of the repulsive electric force exerted on it by the nuclear charge. The recoil of a heavy nucleus is comparatively small.

Before this important experiment, many men thought that the atom was simply a little round sphere containing a mixture of positive and negative charges. Rutherford sought to test this conception by a study of the way in which alpha particles bounce off atoms. His apparatus was arranged so that a narrow beam of alpha particles could strike a very thin foil of metal, like gold. With the aid of a zinc sulfide screen and a microscope on a movable support, he found that nearly all of these helium atoms went straight through the thin foil. However, when he moved the microscope and the zinc sulfide detector to the sides, as in Fig. 471, he discovered that some of the alpha particles had been deflected from their straight paths by the atoms in the foil, or, as we say, they were "scattered." This is just what the cloud chamber photograph of Fig. 469 indicated had happened in a gas. As a matter of fact, some of Rutherford's alpha particles were even bounced backward.

The only way the number of large deflections could be accounted for was on the assumption that the alpha particles had been deflected by some very concentrated charged body, tiny as compared with the over-all size of the gold atom and yet heavy

compared with the alpha particle. Knowing that the light negative electrons could not possibly do this, Rutherford concluded that the heavier positive charges in the gold atom must be grouped together in a central core, or nucleus. Calculations assuming the inverse square law of electrical repulsion showed that, if this positive central nucleus were less than 10^{-12} cm in diameter, helium nuclei striking it should be scattered in the observed fashion.

Thus was born the concept of a nuclear atom. The nucleus, that tiny central "sun," has a number of elementary positive charges equal to the ***atomic number*** (usually called Z), and around it in the neutral atom are enough negative electrons to balance the nuclear charge exactly. The number of electrons, therefore, also equals the atomic number Z. The outermost electrons must be at comparatively great distances from the nucleus, for the atom itself, as we recall, is more than 10^{-8} cm in diameter, more than 10,000 times the nuclear diameter. Actually, of course, if the nucleus is drawn the size shown in Fig. 472, the outer electrons would be about one city block away! The atom is almost entirely open space!

HIGH-ENERGY PARTICLES

In the radiation phenomena with which we have dealt, the energy changes in individual atomic processes increase as the processes take place nearer and nearer the center of the atom. If we consider the energy which is released or absorbed per particle involved, nuclear changes such as radioactive emission are in a completely different class from ordinary physical and chemical processes.

The Electron-volt. In dealing with atomic particles, it is convenient to use a new unit of energy, the ***electron-volt.*** Fortunately, this unit is very easy to visualize. Suppose that we have two plates in a vacuum with a potential difference of one volt between them. Now if an electron starts at the negative electrode, its speed will continually increase until it strikes the positive electrode, and because the potential difference between the electrodes is one volt we say that the total kinetic energy ($\frac{1}{2}ms^2$) acquired by the electron is ***one electron-volt.*** Recalling our basic ideas of electric potential, the work done on any particle of charge e accelerated through a potential difference of V volts will be just Ve. If the particle starts from rest and no energy is lost in collisions with other par-

ticles, Ve will be just the kinetic energy gained, so

$$\frac{1}{2}ms^2 = Ve$$

This energy will be in electron-volts (abbreviated EV) if the unit

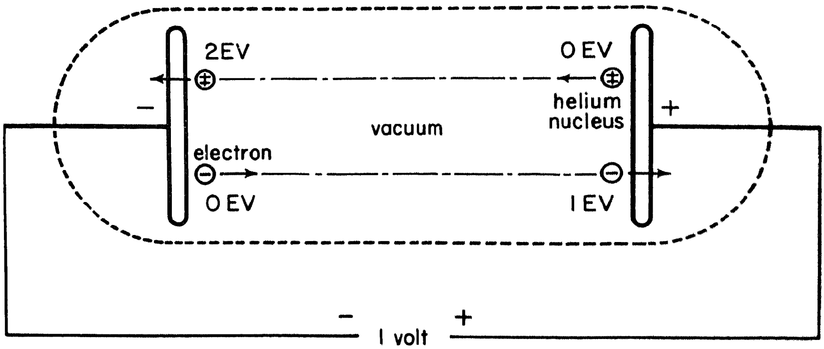


Fig. 473. One electron-volt (EV) is the energy gained by a singly charged particle when it is accelerated without collision through a potential difference of one volt. A doubly charged particle would gain two electron-volts, triply charged, three electron-volts, etc. Thus an electron (bottom) would gain one electron-volt when accelerated (from negative to positive) through a potential difference of one volt. The helium nucleus (top) gains two electron-volts of energy when accelerated in the reverse direction.

of e is the charge of one electron. Of course the mass of a single particle is small, so that the electron-volt is small compared with a joule or foot-pound.

Let us get an idea of what some ordinary energy changes are in terms of electron-volts. An oxygen or nitrogen molecule in the air, traveling at 1,500 ft/sec, has an energy of only about $\frac{1}{30}$ EV. In an ordinary chemical reaction, in a storage cell, for example, where the potential is 2 volts, the energy change per atom is 2 EV. When a molecule of coal combines with oxygen in burning, about 5 EV of energy is liberated. Energy of about 13 EV is required to pull an electron loose from a hydrogen atom, that is, to ionize the atom. Ordinary physical and chemical processes which involve the outer electrons of the atom have energies of this general order of magnitude.

As we learned in our study of X rays, in the heaviest atom, uranium, energy of about 100,000 EV is required to remove the electron closest to the nucleus. Likewise, when an exterior electron gives up its energy and falls into a vacated place in the inner orbit, the X-ray quantum emitted has an energy, $E = hf$, of about

100,000 EV. This is 20,000 times the energy involved in burning a molecule of coal.

Energy changes which occur in the atomic nucleus are of a much greater magnitude than those we have just considered. The

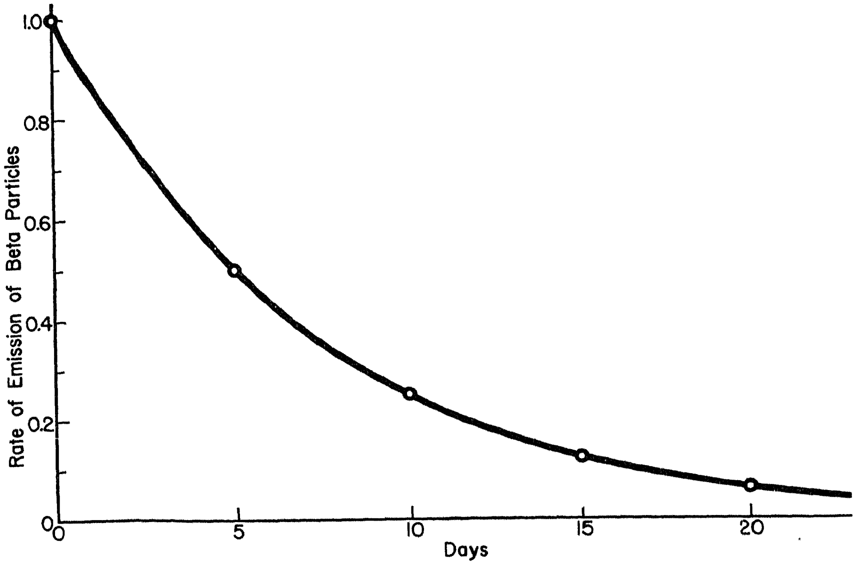


Fig. 474. Radioactive materials decay "exponentially." For an initially pure sample of radium E (Ra E), the number of radioactive disintegrations per second decreases to one half its initial value in 5 days, to one quarter in 10 days, to one eighth in 15 days, to one sixteenth in 20 days, etc. Accordingly, the half-life of Ra E is said to be 5 days.

alpha particle from polonium (Ra F), for example, has the tremendous speed of about 1.5×10^9 cm/sec, about $\frac{1}{20}$ the velocity of light, which corresponds to an energy of 5,250,000 EV. Since energies released in nuclear processes are usually of this general magnitude, physicists, for convenience, often use the term MEV to denote million electron-volts. On this basis, the Ra F alpha particle has an energy of 5.25 MEV.

Radioactive Disintegration. Just as atomic spectra gave information about the structure of the outer part of the atom, a great deal has been learned about the interior of the nucleus by studying the fragments ejected by naturally radioactive nuclei. When one of these nuclei disintegrates, that is, throws off a charged particle, it is changed to a different kind of nucleus because its charge and

mass are changed by the loss of an alpha particle or beta particle.

If a large enough quantity of a pure radioactive element is isolated, it is found that during each second an almost constant fraction of its atoms disintegrate. The disintegrations follow the laws of pure chance. One particular nucleus might not disintegrate for a million years, while within one second its neighbor might fling out an electron and so change into another nucleus. All that can be predicted is that, ***on the average,*** a certain constant fraction of the radioactive atoms present disintegrate during equal intervals of time. For example, if a sample of radium E (Ra E) is observed for a few weeks, the number of electrons per minute gradually decreases, as shown by the curve in Fig. 474. In about 5 days, the rate of emission drops to $\frac{1}{2}$ the original value; in the next 5 days $\frac{1}{2}$ of the remaining Ra E atoms disintegrate, so that the total number left is only $\frac{1}{4}$ of the original number. In 15 days $\frac{1}{8}$ of the Ra E atoms are left, in 20 days $\frac{1}{16}$ are left, etc.

The time required for half of a group of similar radioactive atoms to disintegrate is called the ***half-life*** of that particular radioactivity. This half-life differs enormously for different kinds of radioactive nuclei. For radium C′ it is only about 1 /1,000,000 sec, but it is 4,500,000,000 years for uranium.

Radioactive Processes. From researches extending through several decades, it has become known how the radioactive elements disintegrate. It is important for us to understand what happens in such processes. The heaviest known element, uranium, has an atomic weight of about 238—instead let us say, rather, a ***mass number*** of 238, the whole number nearest the atomic weight. The atomic number of uranium is 92, that is, there are 92 elementary charges in its nucleus; so we can describe the uranium nucleus by writing

$$\text{atomic number} \rightarrow {}_{92}\mathrm{U}^{238} \leftarrow \text{mass number}$$

Alpha-particle Emission. Now when a uranium nucleus emits an alpha particle, that is, a helium nucleus of mass number 4 and 2 units of charge (${}_2\mathrm{He}^4$), the mass number of the original nucleus must decrease 4 units to 234 and the charge must decrease 2 units to 90. Physicists now use the following shorthand description of this process

$${}_{92}\mathrm{U}^{238} \rightarrow {}_{90}(\text{uranium } X_1)^{234} + {}_2\mathrm{He}^4$$

This short symbolic statement is regarded as equivalent to the long sentence that preceded it. Note that, in the case of either mass numbers or charges, the sum of the values for the emitted helium nucleus and the new nucleus is just the value for the original

Element	Mass No.	Atomic No.	Emission	Half-life	α range cm air	α energy MEV
UI	238	92	α	4.4×10^9 years	2.73	4.049
UX_1	234	90	β	24.5 days		
UX_2	234	91	β	1.14 min.		
UII	234	92	α	1.17×10^5 years	3.28	4.626
Io	230	90	α	8.3×10^4 years	3.194	4.545
Ra	226	88	α	1600 years	3.389	4.744
Rn	222	86	α	3.825 days	4.122	5.441
RaA	218	84	α	3.05 min.	4.722	5.972
RaB	214	82	β	26.8 min.		
RaC	214	83	β α	19.7 min.	?	?
RaC^{I}	214	84	α	$(3 \pm 1.5) \times 10^{-6}$ sec.	6.971	7.633
RaC^{II}	210	81	β	1.32 min.		
RaD	210	82	β	22 years		
RaE	210	83	β	5.0 days		
RaF	210	84	α	140 days	3.925	5.253
RaG (lead)	206	82		stable		

Fig. 475. Uranium-radium radioactive series.

nucleus. In other words, there is a "balance" both of mass number and of nuclear charge.

Beta-particle Emission. The new nucleus $_{90}(\text{uranium } X_1)^{234}$ is also unstable and emits a beta ray, or electron, which has a charge of -1. Therefore, the nucleus formed in this process must have a positive charge 1 unit greater (since it has ***lost*** one ***negative*** unit of charge). However, the mass of an electron is so small (1/1,850

unit of mass) that the final nucleus still has the same mass number, 234. This disintegration can be expressed

$$_{90}(\text{uranium } X_1)^{234} \rightarrow {}_{91}(\text{uranium } X_2)^{234} + {}_{-1}(\text{electron})^0$$

Again, there is a balance of initial and final mass numbers and nuclear charges.

The gamma rays emitted during either alpha- or beta-emitting types of nuclear explosion are really by-products and, of course, do not change the nuclear charge or the mass number.

Radioactive Series. The nucleus, initially uranium, which we followed through two disintegration processes, then undergoes many more transformations in each of which an alpha particle or a beta particle is emitted. In all, after 14 such steps, it finally becomes Ra G which is an ordinary lead (Pb) nucleus (atomic number 82, mass number 206). What an exciting journey, and what a humdrum existence thereafter!

Besides the uranium series, two other series of natural radioactive elements exist, the thorium and actinium series, both of which go through somewhat similar processes. The chart of Fig. 475 shows all the steps in the uranium series, with some detail about the radiations emitted and the half-lives of the various products.

Age of the Earth. It is noteworthy that the most satisfactory method of estimating the age of geological formations is to use the radioactive series as a "geological clock." If, for example, in a rock which contains uranium all the lead is Ra G (see Fig. 475), it presumably has come entirely from the disintegration of uranium. Since the rate of disintegration of uranium into lead (Ra G) is known, the age of the rock can be calculated from the relative amounts of lead and uranium which it contains. Some rock formations are so old that a considerable fraction of the original uranium has changed to lead, and analyses of these indicate an approximate age of 2 billion years. Of course, other formations are much younger —less than 100 million years old. The same "geological clock" applied to meteorites from space also usually gives a value of about 2 billion years. The earth and very likely our whole solar system must then be at least of this same age. Measurements of the amount of helium trapped in nonporous radioactive minerals indicate the number of alpha particles—helium nuclei—emitted since formation. This makes possible another calculation of age which agrees quite well with the first value.

POSITIVE RAYS AND ISOTOPES

Weighing the Atom. The ingenious experiments of Crookes, Thomson, Millikan, and others, which we reviewed in Chap XV,

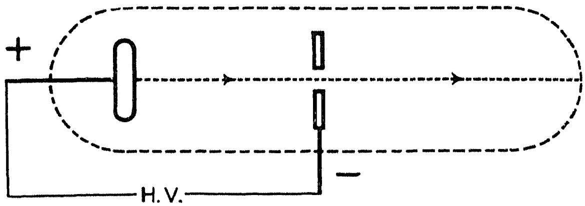
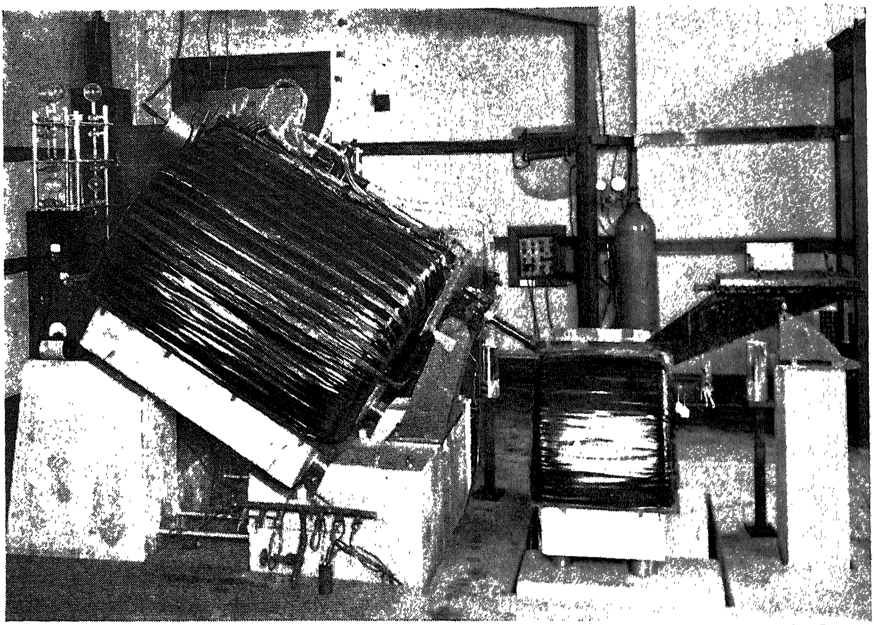


Fig. 476. Positive-ion beam produced in a discharge tube having a perforated cathode.

gave a great deal of information about the nature of one important building block of the atom—the negative electron.

At the same time that the early experiments were being performed with cathode rays in gas discharge tubes, it was realized that after a negative electron is torn loose from a neutral gas molecule something must also be happening to the residual positive part of the disrupted molecule. It was soon shown that the positive "ions" would go through a hole in the cathode (negative electrode), and emerge on the other side. Sir J. J. Thomson was the first to use magnetic and electric fields to determine the nature of these positive rays, and he soon found that here was a new kind of mass balance for weighing atoms and molecules. The ratio of mass to charge of the positive ions could be determined just as for cathode rays or electrons. If no more than electrons were torn from an atom, the heavier positive residue still contained practically all the atomic mass (as has been mentioned before, an electron has a mass only 1/1,850 that of even the lightest atom, the hydrogen atom). In any case, the tiny weight of the one or more electrons could be allowed for and the weight of a whole atom determined.

Long before this, chemical methods had already given a quite accurate measure of the relative masses of atoms. For convenience, oxygen was taken to have a mass of 16.0000 ***mass units,*** and all other atomic masses were referred to it as a standard. By chemical means many elements were found to have approximately integral atomic masses, for example, hydrogen 1.0081, helium 4.0039, and carbon 12.0040. The fact that the atomic masses were nearly whole numbers had led an English physician, Prout, in 1815, to suggest



(E. B. Jordan.)

Fig. 477a. Large mass spectrograph at the University of Illinois.

that all the kinds of atoms are built up of various numbers of a single elementary unit. Prout thought that this unit must be the hydrogen atom because that atom has a mass of unity. However, many atomic masses are not whole numbers—for example, neon 20.183, chlorine 35.46—so by 1900 Prout's hypothesis had been laid on the shelf.

Isotopes. Thomson put neon gas in his positive ray apparatus, and to his surprise found that there were two traces on a detecting screen. The strong trace corresponded to mass 20 and the weaker line to mass 22. Later, there was discovered a still fainter line corresponding to mass 21.

At last the explanation for the nonintegral chemical masses began to dawn. Neon must be a mixture of three kinds of atom with the same chemical properties but with masses that differ by one unit. The chemical atomic mass is of course the average value for the mixture of atoms, and therefore is somewhere between 20 and 22, depending on the relative numbers of each type of atom. Soon chlorine was shown to be of a mixture of two types of atom with atomic masses 35 and 37, respectively.

Atoms differing in this way, that is, atoms of the same element (thus having almost exactly the same chemical properties) but with atomic masses differing by one or more units, came to be called *isotopes.*

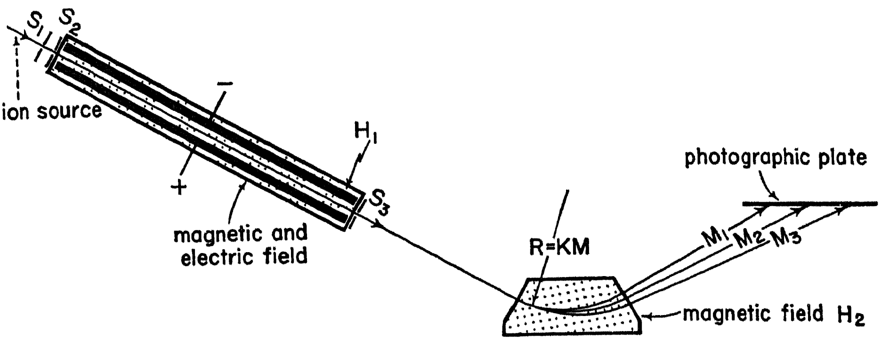
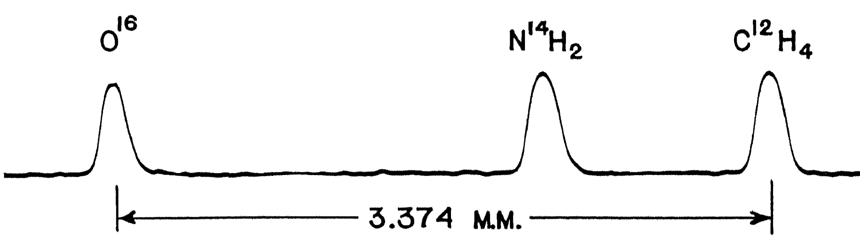


Fig. 477b. Diagram of mass spectrograph shown in (a). At the left is the velocity selector. Positive ions from a discharge tube enter the magnetic field H, combined with the electric field between the charged plates. These fields produce opposite and equal deflections for ions which have the same speed—other ions cannot get through the exit slit S_3. The selected ions are then deflected in the strong magnetic field H_2. The deflection is smaller the greater the mass.

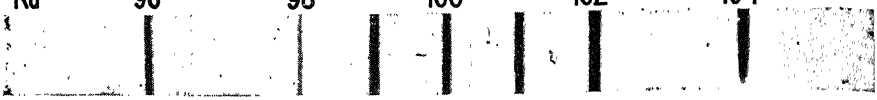
The mass spectrograph is so sensitive that atoms which differ by only one-millionth of a mass unit fall at different spots on the photographic plate.



(*E. B. Jordan.*)

Fig. 477c. Typical record of intensity variation on a photographic plate in the mass spectrograph of Fig. 477a. The atomic mass of O^{16} is 16.0000, that of $N^{14}H_2$ is 16.0238 and that of $C^{12}H_4$ is 16.0364. Thus the total variation across this record is only 0.0364 mass unit.

Mass Spectrographs. As the interest in atomic structure and atomic nuclei developed, experimenters, first Aston at Cambridge, then Dempster at Chicago, Bainbridge, and others, refined and improved Thomson's early instruments so much that atomic weights can now be determined much more precisely from deflections of positive ions in electric and magnetic fields than by ordinary chemical methods. The first step in operating any of the instruments



(*A. J. Dempster.*)

Fig. 478. Mass spectrograph record of the isotopes of ruthenium (atomic mass 101.7). The mass number scale is indicated above the traces corresponding to the various isotopes. Note that isotopes numbers 97 and 103 do not appear, and that 98 is the least abundant.

of these workers is to produce from an electric discharge a stream of positive ions of the element to be investigated. A narrow pencil of these rays, limited by means of slits, is then passed through electric and magnetic fields which effectively separate ions that have different masses but the same charge. These separated beams finally strike different spots, for example, on a photographic plate.

Figure 478 shows a typical record for ruthenium on a plate made by Dempster. Here seven different traces are obtained, showing that ordinary ruthenium, of atomic mass 101.7, is a mixture of different isotopes with mass numbers ranging from 96 to 104. The densities of the lines show the normal relative abundances of these isotopes, the heaviest line being produced by the most abundant.

An element, then, is usually only a family of similar atoms having different atomic masses, in other words, a family of isotopes. A few elements such as aluminum and phosphorus seem to have only one isotope, but most elements have several. Tin has as many as ten. Some 280 stable isotopes are now known, an average of about three for each of the 88 natural elements.

Heavy Hydrogen. One of the most important isotopes is that of heavy hydrogen, now called ***deuterium*** (D). The deuterium atom has a mass number 2, as compared with 1 for ordinary hydrogen. This isotope was first discovered by Urey, Brickwedde, and Murphy at Columbia University through the presence of a very faint spectral line close to a strong line for ordinary hydrogen. All natural hydrogen contains about one part in 5,000 of heavy hydrogen. When combined with oxygen, deuterium forms ***heavy water,*** which is D_2O instead of H_2O. Deuterium is interesting because, next to hydrogen, it has the simplest of all atoms, and the study of its nucleus has contributed much to the general theory of nuclear structure. It has been especially useful in "atom smashing" experiments.

All isotopes of the same element have the same atomic number, that is, each has the same amount of positive charge on the nucleus and also the same number of electrons around the nucleus. Only the ***nuclear*** masses are different. In the shorthand atomic notation described earlier, it is easy to distinguish between isotopes of the same element. For example, the carbon isotopes of atomic number 6 and isotopic mass numbers 12 and 13 are described by the symbols

$$_6C^{12} \qquad \text{and} \qquad _6C^{13}$$

Just to show the accuracy with which physicists are now able to measure the masses of atoms, the values for a few light atoms are given in the following table. As a basis, the mass of $_8O^{16}$ is taken to be exactly 16.00000. Note that the atomic masses are nearly, but not quite, whole numbers.

MASSES OF SOME STABLE ATOMS

Atomic no.	Element	Symbol	Mass no.	Atomic mass (O^{16} = 16.00000)	Relative abundance, per cent
0	(Neutron)	$_0n^1$	1	1.00893	
1	Hydrogen	$_1H^1$	1	1.00812	99.98
	Hydrogen (Deuterium)	$_1D^2$	2	2.01472	00.02
2	Helium	$_2He^3$	3	3.01704	10^{-7}
	Helium	$_2He^4$	4	4.00389	100.00−
3	Lithium	$_3Li^6$	6	6.01690	7.9
	Lithium	$_3Li^7$	7	7.01804	92.1

You may be surprised that the table includes the ***neutron,*** which is a neutral particle with mass only slightly greater than that of a hydrogen atom, but, as we shall see, it is such an important constituent of atomic nuclei that its characteristics may profitably be kept in mind.

Equivalence of Mass and Energy. Exceedingly important ideas which throw much light on the whole question of the relation between matter and energy have come out of the theory of relativity.

Mass Increases with Speed. One relativistic concept is that the mass of a moving body increases with the speed of the body. Fortunately for workers in theoretical mechanics, this increase is very small at speeds we encounter in daily life. Unless the speed gets up to about one-tenth the speed of light, not much mass change is

noticed. When the velocity of a particle approaches that of light, however, as when fragments are ejected from atomic nuclei, the mass change becomes large.[1] An electron traveling with a speed of 2.6×10^8 meters/sec (thus having a kinetic energy of 0.5 MEV) has a mass twice as great as when it is at rest. Many experiments have verified this idea which was of theoretical origin.

Mass and Energy Are Interchangeable. An even more valuable concept from the relativity theory is that of the equivalence of matter and energy. Einstein suggested that any object which has mass has an inherent equivalent energy expressed by

$$\text{Energy} = \text{mass} \times (\text{velocity of light})^2$$

At first this seems quite startling, but experiments done in the last few years have fully confirmed the idea. If the equivalent energy could be completely released from a handful of ordinary matter, it would be truly enormous. In one kilogram of any material, for example, the energy is

$$1 \text{ kg} \times (3 \times 10^8 \text{ meter/sec})^2 = 9 \times 10^{16} \text{ joules}$$

or

$$2.5 \times 10^{10} \text{ kilowatt-hours}$$

The energy in only 1 kg (2.2 lb) of material, if available, would run the power plants of New York City for more than a year! The fact remains that we have not yet succeeded in releasing more than a tiny fraction of this vast store of energy.

Building Elements. Some idea of the value of the concept of equivalence of mass and energy can be obtained by looking more closely at the accurate values of the masses of the isotopes on page 601. How, for example, might deuterium be formed from lighter particles?

Let us accept for the moment the idea, which recent work justifies, that atomic nuclei are built of two kinds of units, the nucleus of the hydrogen atom, which is the ***proton,*** and the ***neutron.*** Then the deuterium nucleus should consist of a proton and a

[1] Actually, if the mass is m_0 at zero speed (m_0 is the *rest mass*), the mass m increases with speed s according to the equation

$$m = \frac{m_0}{\sqrt{1 - \frac{s^2}{c^2}}}$$

where c is the velocity of light, 3×10^8 meter/sec.

neutron, so let us see whether the mass of an atom of H^1 plus a neutron equals the mass of an atom of deuterium.

$$\begin{array}{r l} H^1\text{:} & \text{charge 1, mass 1.00812;} \\ \text{Neutron:} & \underline{\text{charge 0, mass 1.00893;}} \\ \text{Sum:} & \text{charge 1, mass 2.01705.} \end{array}$$

Putting these two particles together would give something with a nuclear charge of 1, which is correct for the deuteron. The added masses, however, give 2.01705, whereas the measured mass of the deuterium atom is only 2.01472. What has happened to the extra mass? Relativity says that, when the proton and neutron are combined, part of their mass is converted into energy, which holds the deuterium nucleus together. Here the 0.00233-unit discrepancy in mass is equivalent to about 2.2 MEV of "binding energy" in the deuterium nucleus. It actually has been verified experimentally that an energy of 2.2 MEV is required to break apart this nucleus.

We shall see further applications of the revolutionary view that mass and energy are equivalent.

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SUMMARY

In 1896, Becquerel discovered ***radioactivity.*** The Curies, Rutherford, and Hahn were prominent in its development. The ***uranium, thorium,*** and ***actinium*** radioactive series were found. Radioactive radiations were called ***alpha rays*** (high-speed helium nuclei), ***beta rays*** (high-speed electrons) and ***gamma rays*** (high-energy quanta). Their ability to penetrate matter increases in the above order. They were identified by behavior in electric and magnetic fields.

Individual radioactively emitted particles are observed by the zinc sulfide ***scintillation screen,*** the ***particle counter,*** and the ***cloud chamber.*** Automatic recording methods have been devised for the counter and cloud chamber.

Rutherford conceived the ***nuclear*** atom from the way alpha particles are deflected in thin foils. The nucleus is tiny, contains most of the atomic mass, and has a number of elementary positive charges equal to the atomic number. Radioactive radiations originate in the nucleus.

The ***electron-volt*** (EV) and ***one million electron-volts*** (MEV) are often used as units of energy of particles. Radiation from nuclei frequently has energies of millions of electron-volts.

For each radioactivity, the average time for half the nuclei of a specimen to disintegrate, the ***half-life,*** is a constant. Half-lives range from 10^{-6} sec to more than 10^{9} years.

Each kind of nucleus can be described by the number of elementary nuclear charges (atomic number) and by the ***mass number*** (the whole number nearest the atomic weight). A type of nucleus may be represented

$$_{\text{atomic number}}(\text{symbol})^{\text{mass number}}$$

When a nucleus emits an alpha particle, its atomic number decreases by 2 and its mass number decreases by 4. Similarly, when it emits a beta particle, its atomic number ***increases*** by 1 and its mass number does not change. Gamma rays accompany alpha- and beta-particle emission and influence neither atomic number nor mass number.

Each of the three radioactive series is a sequence of alpha and beta emitters. In the uranium series a uranium nucleus changes successively to a number of other radioactive nuclei and after 14 alpha and beta emissions becomes a stable lead nucleus.

Electric and magnetic deflection of positive ions from a discharge tube has shown that a single element (with a single atomic number) may consist of atoms with different mass numbers—called ***isotopes.*** Accurate measurements of atomic mass are made in ion deflection apparatus called ***mass spectrographs.***

The relativity theory has predicted, and experiments have verified, that a particle's mass increases appreciably as its speed approaches the speed of light. This change is important only for high-speed atomic particles.

Another relativistic concept is that mass and energy are equivalent to each other with the following relation:

$$\text{Energy} = \text{mass} \times (\text{velocity of light})^2$$

This change is important in nuclear reactions. For example, the total mass of the H^1 atom and neutron is greater than that of the deuterium (heavy hydrogen) atom. This discrepancy gives just the energy which holds the deuterium nucleus together.

QUESTIONS

1. What part did Becquerel's discovery of radioactivity play in opening the modern era of physics?
2. Who were responsible for much of the pioneer work with radioactivity? Where were their laboratories?
3. What are the three types of radioactive radiation? How are they identified?
4. What "stops" an ***alpha particle*** in air?
5. What types of apparatus have been developed for the study of radiations from radioactive substances? How do they work?
6. A ***particle counter*** can be made to operate a magnetic relay each time that an energetic particle enters it. Where does the energy required for this operation come from?
7. What is the "track" of a particle in a ***cloud chamber?***
8. What experiment led to the idea of the ***nuclear atom?*** Who performed this experiment?
9. What do we know about the size and other properties of the nucleus?
10. Why do we believe that radioactivity is a nuclear phenomenon?
11. If a helium nucleus is accelerated through a potential difference of 500,000 volts, what will be its final energy in ***electron-volts?***
12. Can you verify the statement that 1 MEV = 1.60×10^{-13} joule? (The charge on the electron is 1.60×10^{-19} coulomb.)
13. What would be the frequency of a 1-MEV gamma-ray quantum?
14. What would be the speed of a 1-MEV alpha particle? (The mass of the alpha particle is 6.60×10^{-24} g.)
15. What fraction of an initially pure sample of radium E (Ra E) will remain at the end of 30 days?
16. What is a ***radioactive series?***
17. What is a symbolic representation of the disintegration of polonium (Ra F) to form lead? Of Ra E to form Ra F?
18. What elementary particles are believed to constitute the nucleus?
19. What are ***isotopes?*** How may their relative masses be measured?
20. What relativistic relations become important in nuclear processes?

CHAPTER XXI

ATOMIC TRANSMUTATION

The possibility of transmuting base metal into gold has been a dream of men ever since antiquity. The alchemists' efforts to change one element to another failed because, as we know now, the available processes were at best limited to the formation of compounds by uniting elements with one another. Even now, our ordinary chemical techniques are much too feeble to affect the central core or nucleus of the atom.

The recent realization of the dream of atomic transmutation has been a major achievement of experimental science. This accomplishment has by no means led to large-scale production of gold, but the increased knowledge of the behavior of matter and energy bound together in the atom's nucleus has suggested many possibilities for great future development. This may ultimately be far more valuable than the ability to produce a metal of little intrinsic usefulness.

The process of atomic transmutation will become clear when we look further into the methods by which nuclei have been studied.

The Attack on the Nucleus. Attempts to explore atomic nuclei have brought out some stubborn difficulties. The nucleus is so nearly infinitesimal in size as compared to the rest of the atom that only some sort of subatomic "probe," or measuring stick, can possibly be effective in studying it. The first successful nuclear attack was made by Lord Rutherford, who, as we learned, fired high-speed helium nuclei (alpha particles) at atoms and determined something about the "size" of nuclei from the way these alpha particles were scattered.

The problem of making a subatomic particle come in contact with a nucleus is a difficult one. The nucleus is such an extremely small target that only a very tiny fraction of the "projectiles"

fired at it can possibly score a hit. Even more important is the enormous repulsive force which the positively charged nucleus exerts on an approaching positive particle. (The negative electron is so light that it has little influence on the nucleus.) If we recall, Coulomb (page 274) showed that the force of repulsion between like charges is inversely proportional to the square of the distance between them.

$$F = K\frac{Q_1Q_2}{d^2}$$

If Coulomb's law holds at such small distances, the electrical repulsive forces would become truly gigantic at about 10^{-13} cm, even though the charges themselves are small.

Fortunately for nuclear investigators, nature provided the means of penetrating these electrical barriers, for alpha particles which have speeds of 1 to 3×10^9 cm/sec or energies of 2 to 10 million electron-volts (2 to 10 MEV) do have enough energy to approach and actually "hit" the nuclei of atoms of low atomic number.

Before the recent development of artificial methods for accelerating particles to high speed, the alpha particles from natural radioactive sources were the only known probes for searching out the secrets of nuclei.

Nuclear Transformations. In 1919, Rutherford discovered a startling new phenomenon. A source of alpha particles was placed in a chamber containing nitrogen gas. Most of the alpha particles simply used up their energy ripping outer electrons off the nitrogen atoms. Occasionally, however, when a high-speed alpha particle hit a nitrogen nucleus squarely, a new particle was ejected, which had a very long range and could be detected by its scintillations on a zinc sulfide screen many centimeters distant. Detailed investigations showed that this new type of particle was actually the nucleus of a ***hydrogen atom,*** or, as we now call it, a ***proton.*** It had been thrown out in the nuclear explosion produced when a high-speed helium nucleus struck a nitrogen nucleus squarely. The first nuclear transformation had been observed!

On an ever-increasing scale, physicists in many laboratories in America and Europe have since been carrying on this type of "bombardment" of atomic nuclei. By "firing" various kinds of

high-speed particles at nuclei, and by using devices such as particle counters and cloud chambers to detect and identify the fragments ejected by the bombarded nuclei, much has been learned about the structure of the nucleus itself. The relation between the energy of a

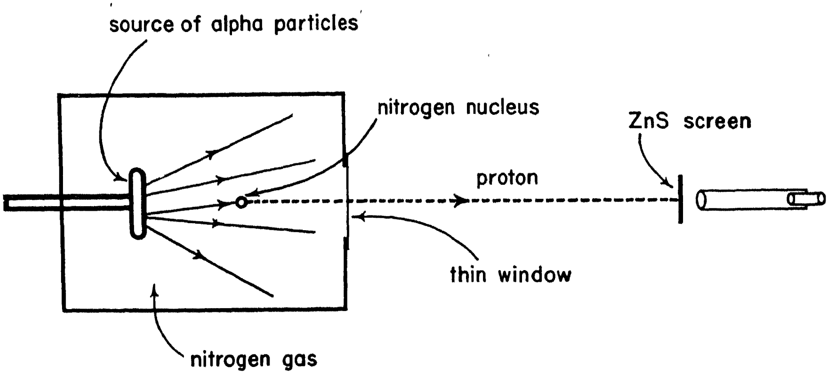


Fig. 479. Rutherford discovered atomic transmutation. Alpha particles speeding through nitrogen gas, but themselves unable to reach the scintillation screen, occasionally liberated particles that had a great enough range to reach the screen. The process was revealed to be the capture of an alpha particle by a nitrogen nucleus and ejection of a proton. The nitrogen nucleus was thereby changed to an oxygen nucleus, but of mass number 17 instead of 16.

bombarding particle and that of the outcoming particles has been most revealing. Before going into this subject, let us first learn something about the new methods used for the artificial production of high-speed particles.

ACCELERATION OF NUCLEAR PROJECTILES

The alpha particles from natural radioactive elements such as polonium (Ra F) and radon (the radioactive gas from radium) served quite well for much of the early work in nuclear disintegration, but it soon became apparent that more powerful sources would greatly extend the range and facility of nuclear experiments. Furthermore, it was desired to learn the effects of other types of projectile not emitted by radioactive sources, the hydrogen nucleus, for example. Many experimenters started to work on methods of giving high energy to nuclear particles.

High-voltage DC Accelerator. The first successful method was the obvious one. If a very high voltage can be generated between two electrodes in an evacuated tube, positive particles of any type are accelerated to high speeds when allowed to pass from the

positive to the negative electrode. Positive ions such as protons or deuterons can be produced by knocking electrons off neutral atoms of hydrogen or deuterium in a low-voltage discharge, whence they can be introduced into the high-voltage tube. If the accelerating potential difference is 1 million volts, then such ions released at the positive electrode will have an energy of 1 million electron-volts (1 MEV) when they reach the negative electrode. The "target" of the material to be bombarded can be placed at the negative electrode. Two serious difficulties had to be surmounted before the method worked: (1) Devices for producing such high voltages had to be developed. (2) Vacuum tubes capable of standing these high voltages had to be devised.

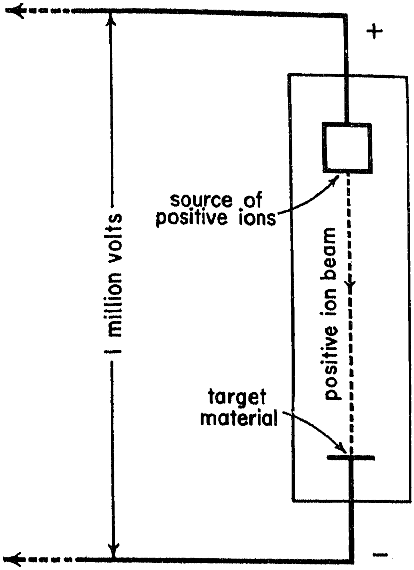


Fig. 480. Positive ions accelerated in a vacuum tube by a potential difference of 1 million volts.

After long experimentation, Cockcroft and Walton, working at Cambridge in England, first succeeded in giving ions enough energy for nuclear bombardment. They constructed a system of step-up transformers and vacuum tube rectifiers to produce 700,000 volts DC for application to the accelerating tube. When hydrogen ions, or protons, were accelerated down the long vacuum tube and directed onto a target of lithium metal, it was observed that helium nuclei were ejected. The first disintegrations by ions accelerated with laboratory apparatus had been produced! This success encouraged many others in America and Europe to generate high-voltage direct current for ion acceleration. The maximum potential difference so obtained has now been pushed up to more than 4 million volts.

Van de Graaff Generators. The Van de Graaff electrostatic generator, which we studied in connection with static electricity (page 277), seemed ideal as a source of steady high voltage. Workers at the Carnegie Institution in Washington first successfully produced

high-energy ions with this type of apparatus. By using a special accelerating tube with a series of many electrodes, it was found possible to minimize "corona" and "breakdown" difficulties and operate at 1 million volts in open air.

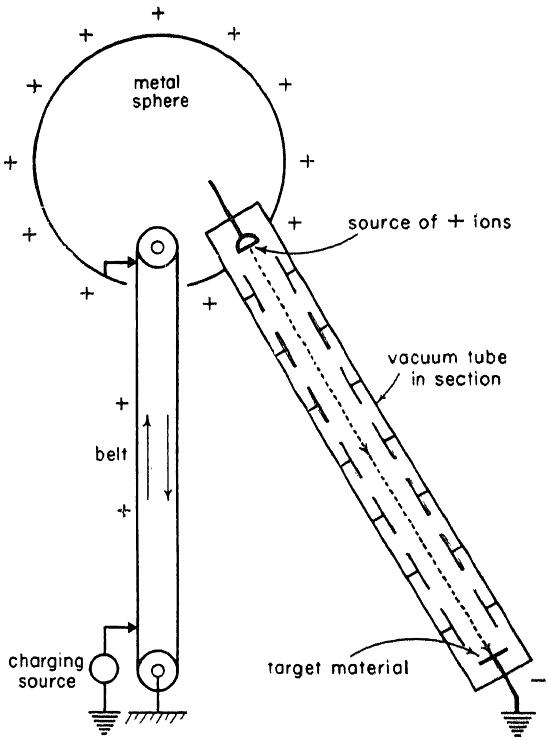


Fig. 481. Electrostatic generator with a vacuum tube for accelerating positive ions (see Fig. 189). High-voltage vacuum tubes are usually divided into many sections with not more than 200,000 volts per section.

More recently there have been constructed in the United States several large electrostatic generators which operate in giant steel tanks containing air or some gas under high pressure. Under such conditions, corona and breakdown difficulties can be reduced so much that operation at 3 to 5 million volts seems feasible.

The Cyclotron. One of the most successful devices with which to produce high-energy particles for nuclear studies is the cyclotron, originally developed by Professor E. O. Lawrence and his coworkers at the University of California. The other types of ion accelerator

produce high-energy particles by sending positive ions in ***one step*** through a very high potential difference. They experience some serious difficulties in producing, controlling, and utilizing the required high voltages. The cyclotron, on the other hand, accel-

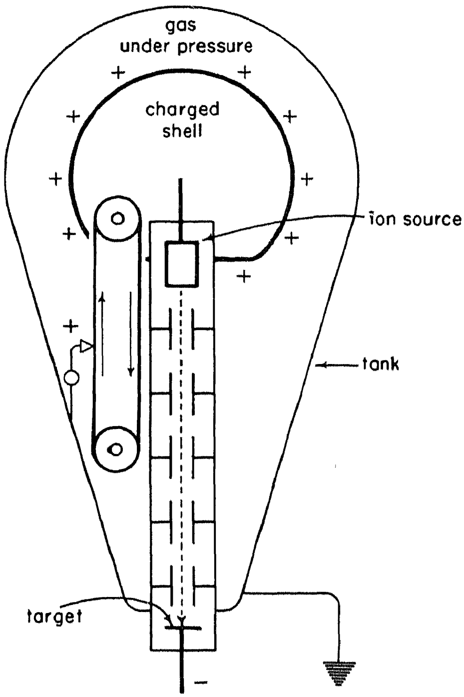
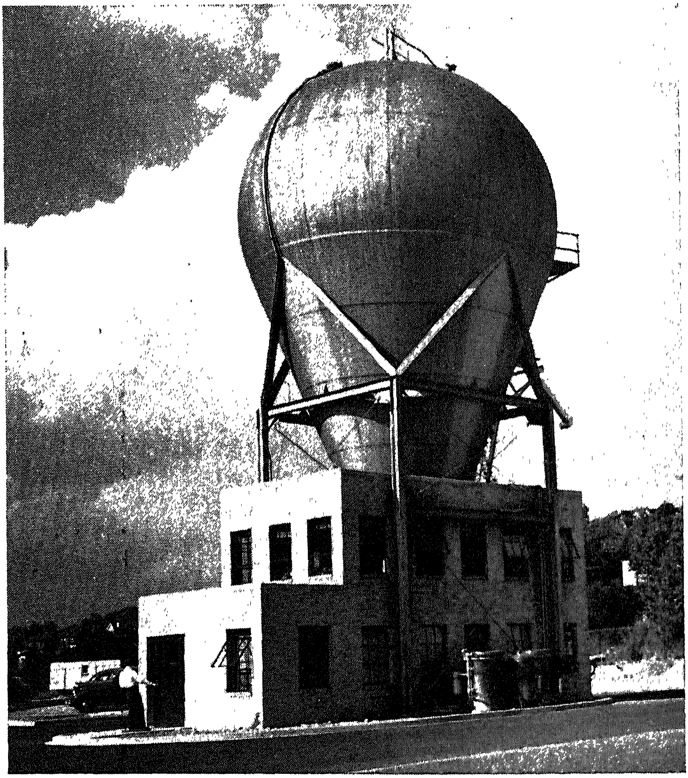


Fig. 482. Electrostatic generator and accelerating tube surrounded by gas at pressure greater than atmospheric to increase operating voltage.

erates ions in ***a succession of many small steps*** each at comparatively low voltage, rather than one step at very high voltage.

The principle of the cyclotron is not difficult to understand. As a simple analogue, imagine a ball B (Fig. 484) on a table top attached by a spring to a peg at the center C. Suppose that two boys with wooden paddles are situated at opposite ends of the line AA'. Now let one boy tap the ball from the side, thus giving it energy. It travels a circular path with radius depending on its speed and the stretch of the spring. Then when the ball traverses a semicircle and crosses the line AA', suppose that the second boy taps it, giving it more energy. It will travel faster and along a circle of larger radius,

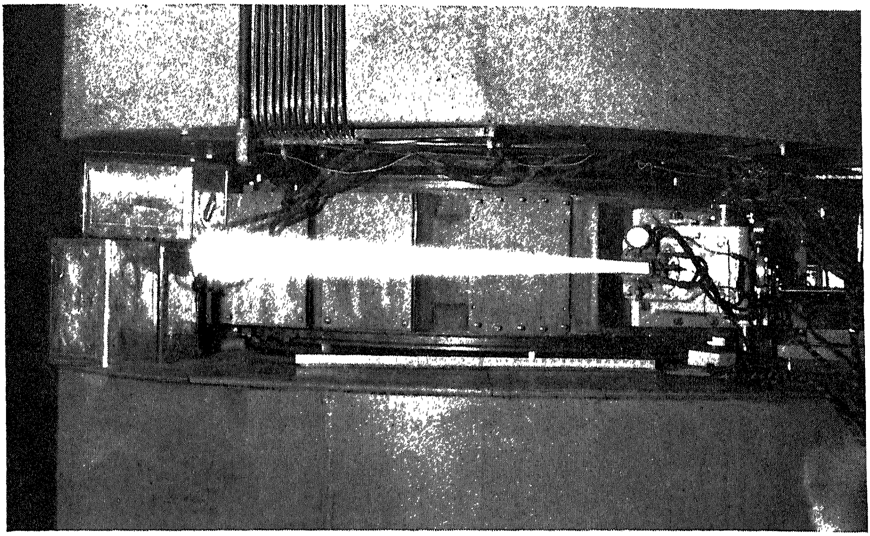
for it pulls harder against the spring. If one of the boys taps it each time it comes around, the ball will gain energy twice each revolution. It will therefore travel in larger and larger semicircles until it acquires a very high energy through a succession of small impulses.



(*Westinghouse Electric and Manufacturing Company.*)

Fig. 483. Four-million-volt electrostatic generator in pressure tank.

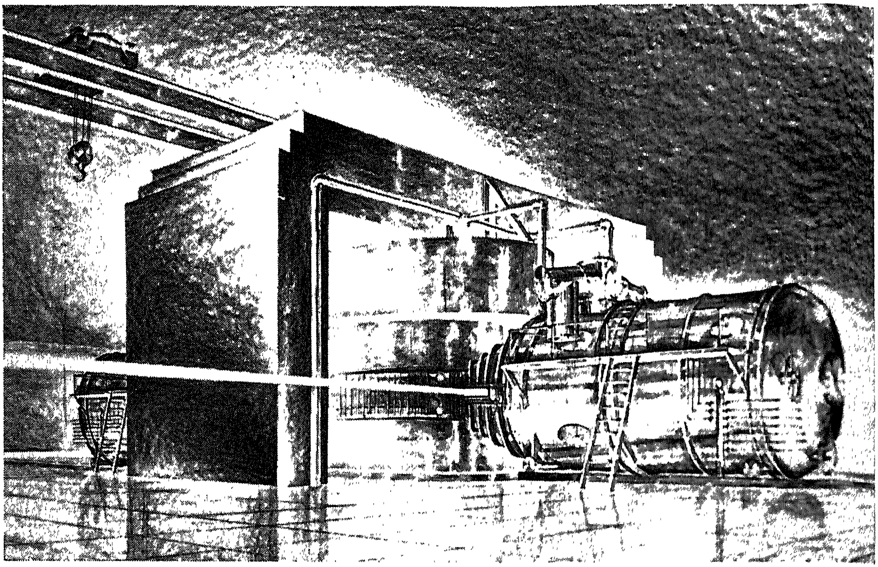
Particles in the cyclotron gain energy in the same general fashion as does the ball on the spring. The force which makes the particles travel in circles is supplied by a strong magnetic field of large area—we have learned in our studies of cathode rays (page 451) that charged particles travel in circles in a magnetic field. The magnetic field thus corresponds to the spring in the mechanical analogue. The "taps" on the ions are produced by a rapidly alternating electric field through which the ions pass twice a revolution. The alternations of the field and the speed of rotation of the ions are adjusted to "keep time" with one another.



(*Donald Cooksey.*)

Fig. 487. 16 MEV beam of deuterons from the largest cyclotron in operation in 1941, the third built by Lawrence and his coworkers at the University of California. The trail of the beam is made visible by ionization produced in air.
The beam emerges from a thin window in the accelerating chamber. Above and below are tanks containing the coils of the huge magnet.

Now, let us see how the cyclotron operates. First, positive ions are produced at the center of the chamber when electrons from a hot filament strike atoms of a gas such as hydrogen, deuterium, or helium. (The gas is often introduced into the chamber near the center at very low pressure, perhaps 1/1,000,000 atmosphere.) A positive ion at the center is attracted to whichever "D" is charged negatively at the moment, and so gains energy and enters the "D." Once inside the hollow metal electrode, there is no electric field, so under the influence of the magnetic field alone the ion travels along a circle of radius depending on the ion's energy. Then, after traversing a semicircle, it again comes into the space between the electrodes, and if conditions are arranged properly the electric field between the "D's" will have ***reversed.*** Thus the ion is attracted now into the other "D," where, as it has gained energy, it travels at a higher speed in a larger semicircle. The net result is that the time of traversal is just the same as it was for the smaller semicircle, so that if the ion was in the first "D" just long enough for the electric field to reverse, it will again find the field reversed on emergence from the second "D."



(Donald Cooksey.)

Fig. 488. Artist's drawing of 4,900-ton cyclotron, now under construction at the University of California.

Following the ion through further revolutions, we see that, if it was started off correctly, it always finds an electric field just right to speed it up whenever it comes into the gap between the "D's," that is, it remains in "synchronism." As a result, the ion is accelerated twice each revolution and travels in ever-larger semicircles until it gains enough energy to traverse a path just within the outer edge of the "D's." Of course, our ion is just one of a great many traveling companions, and finally this group of particles passes through an opening in the edge of one "D." A negatively charged plate is placed here to "pull" the high-energy positive ions away from the edge of the "D," and they may even be directed through a thin vacuum-tight metal foil out into the open air. Here the beam of high-speed projectiles is ready for use—to bombard any desired target and thereby produce nuclear transformations.

To keep the ions and the high-frequency electric field in step, it is necessary that there be exactly the correct relation between the magnetic field intensity and the frequency of the alternating electric field. This is essential because the *magnetic* field sets the time required for the ions to traverse a semicircle, and this must be the same as the time for the *electric* field to reverse its direction.

A beam of hydrogen ions (protons) speeded up by the cyclotron may have a speed corresponding to 30,000 miles/sec, or an energy equivalent to 10 million electron-volts (10 MEV). If the alternating potential difference between the "D's" is 100,000 volts, then, since the particles are accelerated twice each revolution, 50 revolutions (or 100 accelerations) are required to reach 10 MEV.

Thus, by using a comparatively low voltage over and over again, the cyclotron achieves the effect of voltages as yet impossible to work with directly—actually up to 16 million. Even higher energies can be expected in the future. A giant cyclotron, to weigh 4,900 tons and designed to produce 100-MEV ions, is under construction at the University of California.

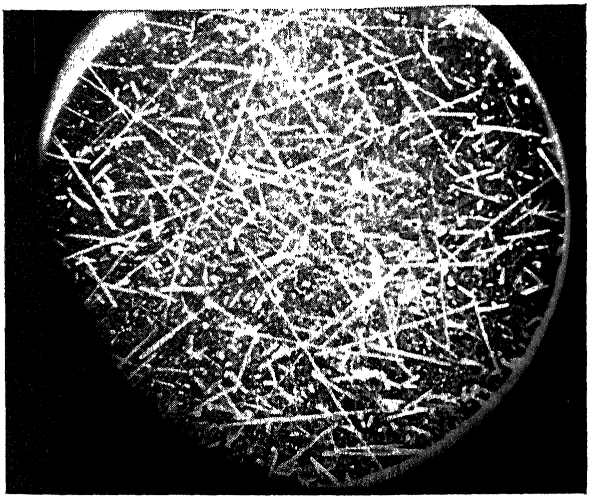
THE NEUTRON

In 1932, at Cambridge, James Chadwick succeeded in showing that a strange new radiation, produced by bombarding certain nuclei with high-speed particles, behaved as though it consists of neutral (uncharged) particles. This type of particle, called the ***neutron,*** was shown to have about the same mass as the proton, the nucleus of the hydrogen atom. The difference is of course that the neutron has no electric charge. According to recent measurements, the neutron has a mass of 1.00893 mass units, while the neutral hydrogen atom (that is, a proton and extranuclear electron) has a mass of 1.00812 units.

Since the neutron has no charge, it behaves quite differently from all other particles we know. It experiences no electrical forces as it goes through matter, so it slips through the outer parts of atoms with the greatest of ease, and can even go through many feet of lead. Were it not that it occasionally collides with an atomic nucleus, we could scarcely detect it at all.

When neutrons pass through a cloud chamber, they themselves leave no visible trace, but we do see cloud tracks which seem to come from anywhere. One of these tracks occurs whenever a neutron happens to hit a nucleus squarely so that the nucleus acquires a fraction of the neutron's energy and is "projected" forward. The neutron and proton have about the same mass, so when the struck nucleus is a proton and is projected directly forward (like one billiard ball struck directly by another) it may acquire practically all the energy of the neutron. For heavy nuclei the energy transferred is much less.

The nuclei thus projected by neutron impacts are charged and, therefore, ionize the gas through which they pass. If we look at a cloud chamber into which neutrons are passing, we see only the tracks of the struck nuclei. Figure 489 is a cloud-chamber photo-



(*F. N. D. Kurie.*)

Fig. 489. Cloud tracks of hydrogen nuclei (protons) projected by energetic neutrons. The neutrons originated at a cyclotron target being bombarded with deuterons six feet from the cloud chamber.

graph in which the long tracks are due to projected protons, and the short dense tracks are due to projected heavier nuclei such as oxygen or nitrogen.

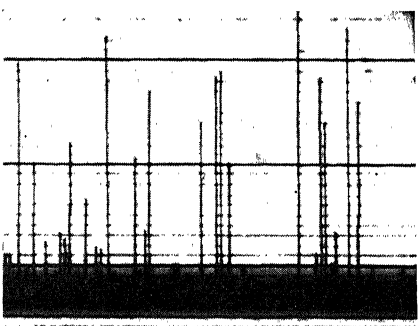


Fig. 490. Oscillograph records of ionization produced by helium nuclei (alpha particles) projected by energetic neutrons. The neutrons were liberated by bombarding beryllium with high-speed protons from cyclotron. Compare with Fig. 467.

The ionization produced by such "neutron recoil" nuclei in an "ionization chamber" filled with hydrogen and connected to a sensitive amplifier is an even more satisfactory way of detecting fast neutrons. The "spikes" on the oscillograph record in Fig. 490 are proportional to the ionization currents produced by individual recoil protons in such an ionization chamber.

The neutron makes an even better "probe" to investigate other nuclei than do charged particles. The way in which neutrons

are scattered in collisions with nuclei has added to our information about effective nuclear sizes.

Neutrons and Protons in the Nucleus. Since neutrons and protons are the fragments most commonly ejected from bombarded nuclei, it is reasonable to infer that these particles are the chief building units of all nuclei. Suppose now that we consider how, on this basis, nuclei might be built up. The proton, symbol $_1H^1$, has charge 1 and mass number 1. This is just the simplest nucleus, the hydrogen nucleus. The deuterium nucleus has charge 1 and mass number 2, so, as we mentioned earlier, it can be one proton and one neutron

$$_1H^1 + {_0n^1} = {_1D^2}$$

giving total charge +1, mass number 2. The nucleus of helium, $_2He^4$, can be formed by two protons to give charge +2, and two neutrons which raise the total mass number to 4. In symbolic form

$$_1H^1 + {_1H^1} + {_0n^1} + {_0n^1} = {_2He^4}$$

Lithium $_3Li^6$ has three protons and three neutrons in its nucleus

$$_1H^1 + {_1H^1} + {_1H^1} + {_0n^1} + {_0n^1} + {_0n^1} = {_3Li^6}$$

Lithium $_3Li^7$ has three protons and four neutrons in its nucleus

$$_1H^1 + {_1H^1} + {_1H^1} + {_0n^1} + {_0n^1} + {_0n^1} + {_0n^1} = {_3Li^7}$$

and so on.

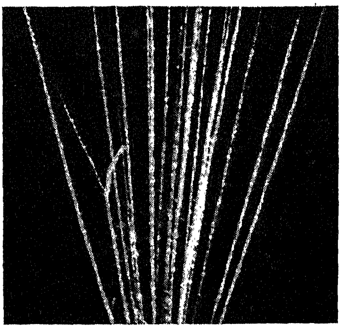
In general for any atom $_zX^m$ where z is the atomic number and m is the mass number:

1. The atomic number z is just the number of protons in the nucleus (or the number of electrons in the neutral atom).

2. The mass number m (the nearest whole number to the exact isotopic mass) is just the sum of the mass numbers of the protons and neutrons, that is, the total number of neutrons and protons. For example, $_{92}$uranium^{238}, the heaviest nucleus, must have 92 protons and 238 − 92 or 146 neutrons.

It can be seen that all atomic nuclei except a few of the lightest have more neutrons than protons. Since the number of protons and electrons in all neutral atoms is equal, there are actually *more neutrons* in the universe than any other particle. This is interesting in view of the fact that the neutron was discovered only a few years ago.

Holding the Nucleus Together. We have noted before that the mass of a nucleus is nearly but not exactly a whole number. In general, the exact mass is *always less* than the sum of the masses of the protons and the neutrons in the nucleus. As we recall, the reason for this is that some of the mass is converted into energy and represents the energy which holds the nucleus together.



(*Blackett.*)

Fig. 491. Cloud chamber photograph showing disintegration of nitrogen nucleus ($_7N^{14}$) by a high-speed alpha particle ($_2He^4$). The heavy branch of the forked track is the newly formed oxygen nucleus ($_8O^{17}$) and the fine branch is the ejected proton ($_1H^1$). Such an impact occurs, on the average, less than once in a thousand tracks.

We saw before that when a proton and a neutron combine to form a deuterium nucleus, nearly 0.0024 mass unit is actually converted into about 2,200,000 EV of energy which hold the proton and neutron together. This is the *binding energy* of that nucleus. Experiments show that this is the energy actually required to tear apart a deuterium nucleus and convert it into a free proton and a free neutron.

You might ask why the nucleus does not fly apart because of the enormous forces with which all the tightly packed positive protons must be repelling each other. New experiments on scattering of protons shot at protons and of neutrons shot at protons show that a strange new type of force comes into play when two protons, or a neutron and proton, or two neutrons are brought very close together. Much remains to be learned about this new force which accounts for nuclei holding together, and many scientists are investigating it. Nevertheless, it is known to be a strong attractive force, which seems to be neither electrical, magnetic, nor gravitational and which shows up only when particles are closer together than about 2×10^{-13} cm. Speculation about its nature has led to the interesting suggestion that neutrons and protons may be but two different states of the same fundamental particle, and that the neutron may be capable of changing into a proton and an electron.

NUCLEAR TRANSFORMATIONS

The "atomic artillery" developed to fire high-speed charged particles has been used to uncover a great deal of information about nuclei.

In order to picture what may occur when a projectile scores a hit on a nucleus, let us take a typical case. Suppose that high-speed helium nuclei, $_2He^4$, from a radioactive source or from a cyclotron, are flung at beryllium, a light metallic element. A few

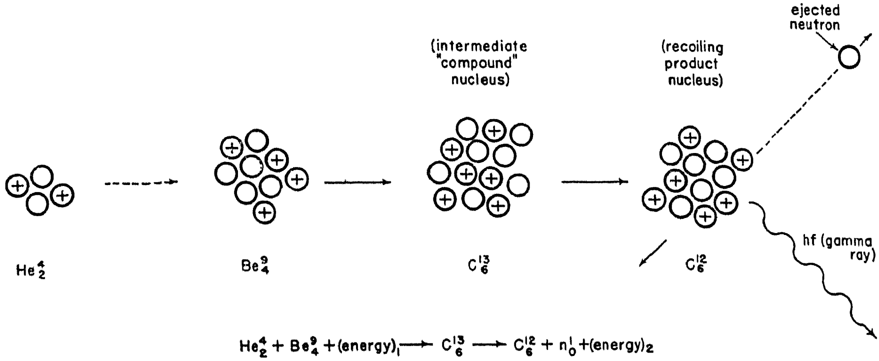


Fig. 492. Schematic description of the nuclear reaction which can occur when a high-speed alpha parlicle strikes a beryllium nucleus to form an ordinary carbon nucleus, after ejecting a high-speed neutron.

of these alpha particles will by chance hit beryllium nuclei, $_4Be^9$, squarely. The alpha particle, which contains two neutrons (indicated ○) and two protons (indicated ⊕), is shown at the left of Fig. 492 as it approaches the beryllium nucleus, which has four protons and five neutrons. Whenever the incident particle can actually overcome the electrical repulsion and come close to the nucleus, the first thing which normally occurs is that the two particles combine to form a new compound nucleus. Since the number of protons in the two original particles add to an atomic number 6, the new nucleus must be carbon. It is a different type of carbon than normal, for the mass numbers add to 13 instead of the usual carbon mass number 12. At least temporarily, beryllium has been transmuted to carbon.

The compound nucleus is sometimes stable, but more often it is unstable and quickly breaks down, ejecting some heavy particle. In the case we are considering, a high-speed neutron is flung out, leaving behind a recoiling carbon nucleus of mass number 12. (Since the neutron has only mass and no charge, the compound nucleus is simply reduced in mass, leaving ordinary carbon.) Often a high-energy gamma-ray quantum (energy = hf) is also emitted during this violent nuclear explosion.

What happens in a nuclear reaction or *transmutation* can be expressed by the type of short notation, much like a chemical equation, which appears below Fig. 492. The process, indeed, belongs to a sort of "nuclear chemistry."

Mass and Energy. The physicist is always interested in what happens to energy, and, in nuclear reactions particularly, he must remember that mass and energy have been shown to be essentially the same thing. Suppose that we see how well the books balance in an actual case, where the beryllium nucleus is bombarded by an alpha particle which has an energy of 7.68 MEV. Since

$$1 \text{ MEV} = 0.001073 \text{ MU (mass unit)}$$

7.68 MEV = 0.00826 MU. We can represent the reaction as,

$${}_2\text{He}^4 + (\text{energy of } {}_2\text{He}^4) + {}_4\text{Be}^9 \rightarrow {}_6\text{C}^{12} + {}_0\text{n}^1 + (\text{energy excess})$$

so

[Mass + energy] input (left-hand side)		[Mass + energy] output (right-hand side)	
Mass ${}_2\text{He}^4$	= 4.00388 MU	Mass ${}_6\text{C}^{12}$	= 12.00398 MU
Mass ${}_4\text{Be}^9$	= 9.01497 MU	Mass ${}_0\text{n}^1$	= 1.00893 MU
Energy ${}_2\text{He}^4$	= 0.00826 MU	Expected energy excess	= 0.01420 MU
Total [mass + energy]	= 13.02711 MU	Total [mass + energy]	= 13.02711 MU

In order to make the total [mass + energy] input equal the [mass + energy] output, the kinetic energy of the ejected neutron, the carbon nucleus, and the energy of the gamma ray (when one is given off) should be 0.0142 MU, or 13.2 MEV. The actual observed total energy, 13.4 MEV, is as close to the expected value as can be measured. This reaction is "exothermic," that is, more kinetic energy is released than was put into the reaction, because some of the mass was converted into energy. The excellent [mass + energy] balance in this and many other reactions shows clearly the accuracy of the concept that mass and energy are equivalent.

We are led to the conclusion that to be precise the laws of *conservation of energy* and *conservation of mass* must be combined in the single statement: *In nature the sum of mass and energy* (*both expressed in the same units*) *remains constant.* This does not apply strictly to either mass or energy alone. However, in all processes except those involving individual nuclei or elementary particles the changes in total mass are so small that we cannot

detect them with our present devices. They therefore go unnoticed. We are quite certain that the mass does change in ordinary chemical reactions where energy is released or absorbed, but the changes are so small that they are not yet measurable.

Many hundreds of nuclear reactions like the one we have considered have been discovered by workers in the last few years. Protons, deuterons (deuterium nuclei), alpha particles, and even neutrons have been hurled at all possible elements, and the results have been studied. We cannot consider all cases in detail, but to summarize them: The bombarding particle is captured and very shortly afterward a neutron, proton, or alpha particle, or in a few cases just a gamma ray, is emitted. This statement covers all reactions but a very few in which more than one particle is emitted by the compound nucleus. Supplementary gamma rays may be emitted in all these processes.

ARTIFICIAL RADIOACTIVITY

New nuclei formed by the many types of nuclear transmutation which have been outlined are not always stable. They are often ***artificially radioactive*** and at some later time emit either negative electrons or ***positive electrons*** before becoming stable.[1] Such artificially radioactive isotopes of ordinary elements have half-lives with values ranging from a fraction of a second to many hundreds of years.

You might ask how it is that a nucleus may emit an electron when we have said that nuclei are made only of protons and neutrons. The question is still not entirely solved, but the best answer seems to be that electrons (positive or negative) are produced only under very special conditions and that they may be formed by the change of a neutron into a proton and a negative electron, or of a proton into a neutron and a positive electron. Some theories postulate that a tiny neutron, a ***neutrino,*** without any charge and of very small mass, takes part in this process. No experimental method so far devised has detected this particle, which (if it exists) seems admirably designed to elude investigators.

The positive electron or ***positron*** was first identified in 1933 by Carl Anderson in some cloud-chamber photographs of cosmic rays (page 641). This particle has the same amount of charge and mass

[1] Some alpha-particle emitters have been made artificially by bombarding various of the heavier nuclei. For example, polonium (Ra F) has been produced artificially.

Fig. 493. Cloud-chamber tracks of positive and negative electrons ejected from artificially produced radioactive elements (negative print). Curved to the left by a magnetic field are negative electrons from radioactive silicon (Si^{31}), and curved to the right are positive electrons from radioactive nitrogen (N^{13}). The source is in the circular well shown at the bottom of each photograph.

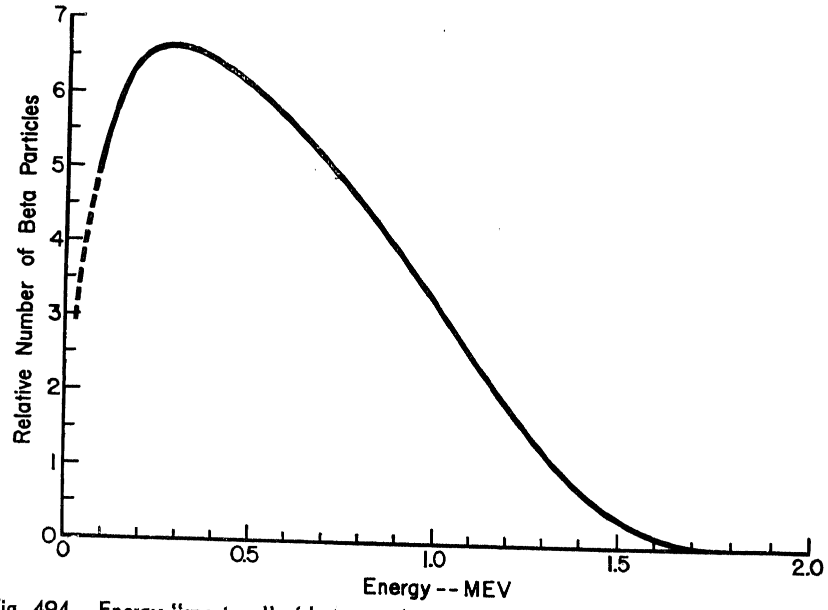
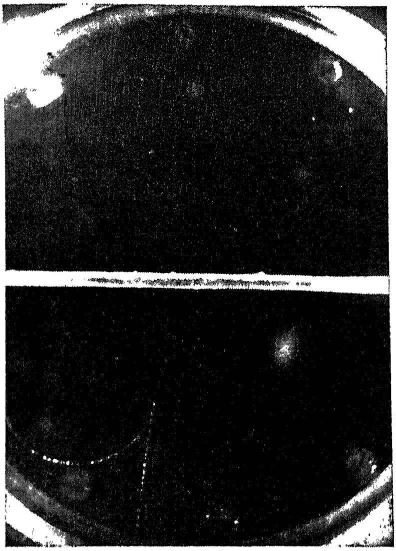


Fig. 494. Energy "spectrum" of beta rays from radioactive phosphorus ($_{15}P^{32}$). This radioactive isotope is produced by bombarding ordinary phosphorus with high energy deuterons. Beta-ray energy distributions are the only continuous spectra "emitted" by nuclei—alpha rays and gamma rays have sharply defined energies. The existence of a neutrino which can share with the electron various proportions of the energy given off in beta-ray emission has been assumed to account for continuous beta-ray spectra.

as an ordinary negative electron, but the sign of the charge is positive instead of negative. One of the most striking ways in which positrons are produced is in the passage of high-energy gamma rays through a cloud chamber. Occasionally a positive and negative electron "pair" is suddenly created. It appears as two tracks which curve in a magnetic field in opposite directions, indicating opposite charges. Experimentalists have found that the [mass + energy] value of the two new particles just equals the energy of the gamma-ray quantum from which they were created. Energy has indeed been converted into matter!

This indisputable production of "pairs" lends plausibility to the idea that positive or negative electrons might be "created" just before emission as beta rays from radioactive nuclei.



(*C. D. Anderson.*)

Fig. 495. Cloud tracks of a positive and negative electron pair produced in the gas of the cloud chamber by a cosmic-ray photon. The positive electron is so energetic that the magnetic field (directed perpendicular to page) deflects it only slightly toward the right. The negative electron, however, has much lower energy as indicated by its strong curvature toward the left.

Slow Neutrons and Artificial Radioactivity. One of the most effective methods of producing radioactive elements is by neutrons. Strangely enough, as Fermi discovered, neutrons are more effective the slower they are. These uncharged particles feel no repulsive forces, and they are attracted to nuclei when they approach within the range of nuclear forces. The more slowly a neutron moves as it goes near a nucleus, the longer is the time during which the attractive force may drag the neutron into the nucleus. Many atomic nuclei show a pronounced "resonance" effect, that is, they capture passing neutrons comparatively readily when the neutrons have just the right energy.

Slow neutrons are usually produced from fast neutrons by allowing the fast neutrons to lose their energy in collisions with the

protons in materials rich in hydrogen, like water or paraffin. Eventually the neutrons become slowed down so that many of them have the same energy as the average for molecules of the material, which corresponds to a kinetic energy of about 1/30 EV.

The process of artificial radioactivity may be illustrated by what happens after slow neutrons bombard platinum. Let us consider only the platinum isotope of mass number 196. Schematically, we may write

$$
\begin{array}{l}
{}_{78}\mathrm{Pt}^{196} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{78}\mathrm{Pt}^{197} + \text{gamma ray} \\
\qquad\qquad\qquad\qquad \downarrow \quad \text{(half-life 18 hr.)} \\
\qquad\qquad\qquad\quad \underset{\text{(gold)}}{{}_{79}\mathrm{Au}^{197}} + {}_{-1}(\text{electron})^{0} + \text{energy}
\end{array}
$$

This means that a platinum nucleus of mass number 196 (${}_{78}\mathrm{Pt}^{196}$), when it captures a neutron (mass number 1), becomes one mass unit heavier, forming platinum of mass number 197 (${}_{78}\mathrm{Pt}^{197}$), and emits a gamma ray. However, ${}_{78}\mathrm{Pt}^{197}$ is not a stable platinum isotope. It is an artificially radioactive isotope of ordinary platinum, with a half-life of 18 hr. It emits a negative electron which has a charge of -1, so the residual nucleus has a charge one unit greater, that is, the atomic number is 79—which means that this new nucleus is ordinary stable gold!

The dream of the alchemists has come true, but there is little danger that the process involved will be commercially successful, considering the relative prices of platinum and gold. By transmutations similar to the one for platinum, almost every known element can now be made artificially radioactive.

The Future of Radioactive Isotopes. Many interesting possibilities are growing out of the production of artificially produced radioactive isotopes. Some of them promise to be of great practical value.

Radioactive Isotopes as Tracers. A radioactive isotope of an ordinary element is usually chemically indistinguishable from its stable neighbors, but electron counters, which we have described, are so sensitive that they can detect the radiation from these radioactive atoms. Thus, an element or a compound can be "tagged" by having a few radioactive atoms mixed with the normal ones, and then the progress of that substance can be "traced" through physical, chemical, biological, metallurgical, or industrial production processes. In all of the fields mentioned, but particularly

in biology, the use of radioactive tracers makes it possible to gain otherwise elusive information about the nature of various phenomena, especially the rates at which they occur. As an example, it was exceedingly tedious to determine by ordinary chemical means that

(P. R. Stout and associates.)

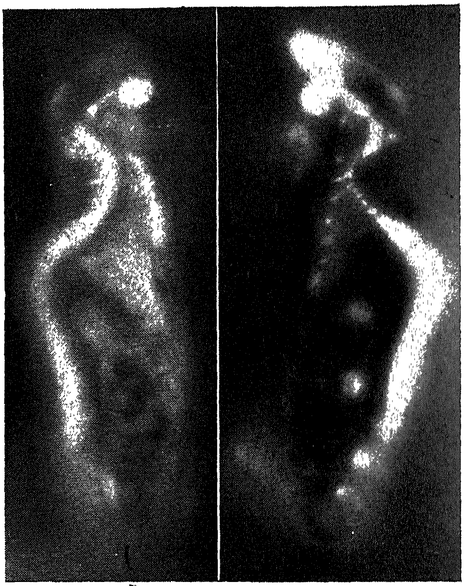
Fig. 496. Radio-autograph of distribution of radio-phosphorus ($_{15}P^{32}$) in leaves of tomato plant. Radio-phosphorus in form of phosphate was placed in nutrient medium of plant and 36 hours later photograph was made by placing leaf on plate. Regions where phosphorus accumulated show up as light areas.

phosphorus in the bones and teeth of adult animals is continually replaced by phosphorus from their food. However, this fact was verified easily by the identification of *radioactive* phosphorus in the bones and teeth of animals to which it had been fed.

Concentrations of stable isotopes such as deuterium are also being used as "tracers" by employing a mass spectrograph to detect their presence in greater than normal proportion. In other words, a sample of an element enriched in a rare isotope, though

having the same general chemical behavior, can be distinguished from any normal sample.

Therapy. Another interesting possibility is that artificial radioactive elements may serve as substitutes for radium in cancer



(*C. Pecher.*)

Fig. 497. Radio-autographs of radio-phosphorus ($_{15}P^{32}$) and radio-strontium ($_{38}Sr^{89}$) in rats. Section of rat is placed against photographic plate a short time after feeding the rat "tagged" phosphorus or strontium compounds. Strontium is shown to be more concentrated in the bony structure than phosphorus which is more generally distributed.

treatment. Such materials as ordinary table salt (NaCl) may be made highly radioactive. These radioactive isotopes are as harmless chemically as their related stable isotopes, and may prove satisfactory for medical treatment in certain cases where radium is unsuccessful. It should be emphasized that these are but possibilities which biological research workers are investigating, and that they are still not entirely proved. However, treatment of certain types of leukemia, a form of cancer, with "radio-phosphorus" has given results which seem to be at least comparable with those from X rays, in controlling the disease.

All forms of cancer treatment by radiations such as X rays and gamma rays from radium depend for their effect on destruction of the cancer cells when energy is released by the radiation and ionization produced in the cancer region. Damage to normal ad-

jacent tissue is minimized as far as possible by shielding screens and other devices. X rays and gamma rays from radium have been used widely with some success.

Therapeutic uses for artificial radioactive elements, and particularly for neutrons which are so effective in releasing energy when they strike nuclei, are now being investigated in a number of research centers. There is also considerable promise that with these new media the cell destruction can be more effectively confined to cancerous tissue. In all, the biological effects of radiation form a rich field for study in which biologists, doctors, physicists, and chemists are cooperating extensively.

"Fission" of Heavy Elements. Early in 1939 a new type of nuclear reaction was discovered. Heretofore all known nuclear processes had involved the emission of only light fragments, such as protons, neutrons, or alpha particles, and the energy releases were at most several million electron-volts.

A vast amount of experimental work finally culminated in showing that when the heaviest elements, uranium, protoactinium, and thorium, are bombarded with neutrons, the resultant nucleus actually "splits" into two fragments of approximately equal mass which fly apart with the tremendous energy evolution of about 200 million electron-volts! In uranium, slow neutrons with an energy of only $\frac{1}{30}$ EV can produce this nuclear catastrophe, but in the other two elements faster neutrons are required. The process came to be called ***fission*** after the analogy with the biological phenomenon of cell division. After violently recoiling, the fragments are still so highly "excited" that they continue to eject a succession of high-speed electrons, neutrons, and gamma rays. The resulting fragments were identified chemically as a variety of pairs of nuclei of medium weight, such as krypton and barium.

Can Nuclear Energy Be Released on a Large Scale? The discovery of fission has focused considerable attention on the enticing possibility of releasing nuclear energy on a large scale, that is, of converting mass into energy. All types of atom smashing other than fission have been quite useless for practical energy release. In firing high-speed charged projectiles from a cyclotron, for example, less than one projectile in 100 ever hits a tiny nuclear target and causes a nuclear transformation. So far, therefore, the ***efficiency*** has always been very low.

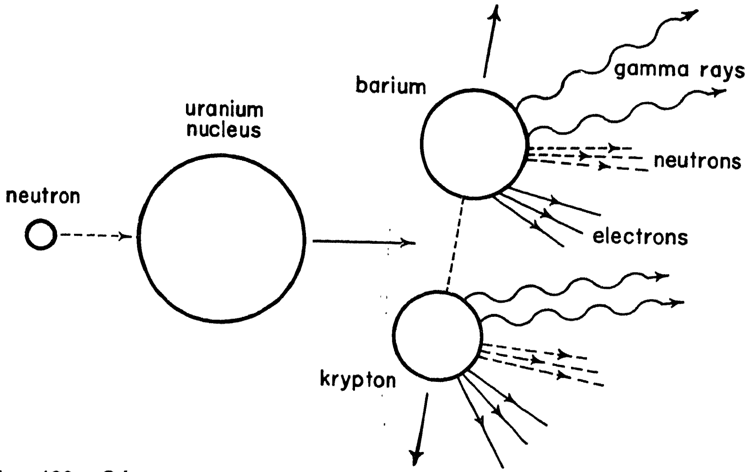
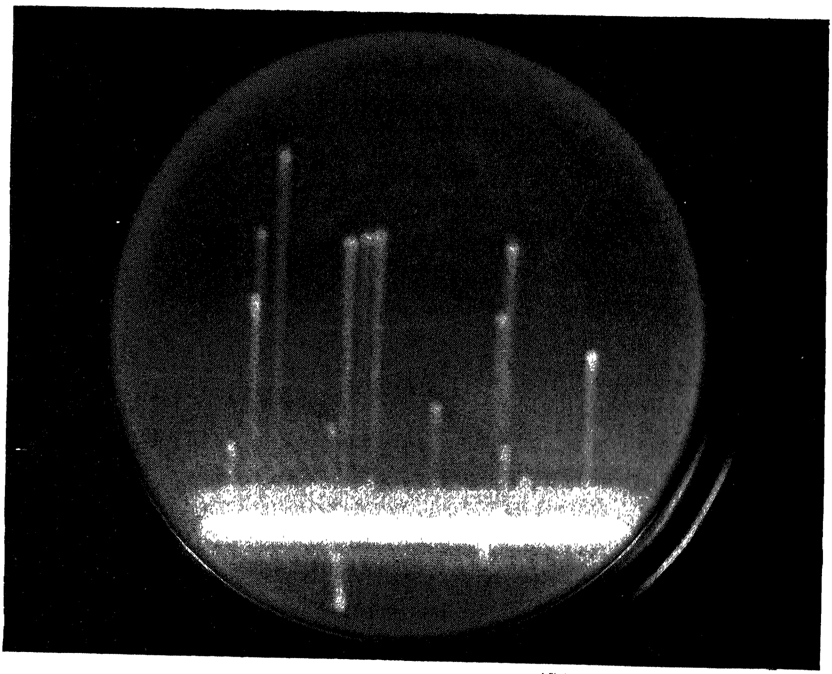


Fig. 498. Schematic representation of fission of a uranium nucleus by a slow neutron. The electrons, neutrons, and gamma rays are actually emitted from the fragments more or less equally in all directions.



(*Columbia—Black Star Photograph.*)

Fig. 499. Oscilloscope record of high-energy fragments from fissions of uranium.

Uranium fission opens up an entirely new possibility because the neutrons emitted by the excited fission fragments can, in principle, go on to produce more fissions, which in turn would release additional neutrons capable of producing still more fissions, and so a large-scale "cascade" process might be built up. On this basis the process would be self-sustaining, that is, once started it would continue indefinitely. The mechanism is actually complicated by a number of factors, and much research is necessary before it can be known definitely whether or not useful energy release can be accomplished.

The discovery that it is the rare uranium isotope of mass 235 (U^{235}) which undergoes fission with slow neutrons, brought out a serious complication in attempts to make practical use of the fission process. Ordinary uranium contains 99.3 per cent of atoms of mass 238, 0.7 per cent of atoms of mass 235, and a very small percentage of atoms of mass 234. In ordinary uranium, the U^{235} is so "dilute" that it must be concentrated before there is much chance for it to take part in a self-propagating fission process. The separation of such a small fraction of U^{235} from the large bulk of chemically similar U^{238} on a practical scale presents enormous technical difficulties which may be insurmountable.

If ever realized, the cascade fission process of releasing atomic energy would be the equivalent of "burning" uranium by combining it with neutrons, just as coal or hydrocarbons are burned by combining them with oxygen. It is interesting to note that on this basis 1 lb of uranium of mass 235 would release energy equivalent to more than 2 million lb of coal! However, even this tremendous energy corresponds to a conversion of only about 0.1 per cent of the mass of the uranium into energy. Whether this or other nuclear reactions can be made to work on earth, and to run the power plants of the future, remains to be seen. Certainly the advances made in that direction already exceed the wildest dreams of physicists ten years ago.

STELLAR ENERGY

In the last analysis we have always been using atomic energy, since our energy comes largely from the sun. Recent experiments in the laboratory have suggested theories which show that our sun and the other stars must obtain their radiant energy from nuclear

reactions which occur at the centers of stars under the extreme conditions of high temperature and high pressure which exist there.

The stars of the "main sequence" in Fig. 85 on page 118, of which our sun is a typical member, all seem to obtain their energy through a series of nuclear reactions in which four hydrogen atoms are combined to form a helium atom, with carbon acting as an intermediary, or "catalyst." About 30 MEV are liberated in this process. The rate of such reactions increases extremely rapidly with temperature, perhaps proportional to T^{18}. Such processes do not occur at ordinary temperatures, but a very tiny fraction of the atomic nuclei do combine and release energy at the temperature of about 20,000,000°C, which all calculations show exists in the sun's core. In spite of the enormous rate at which energy is radiated by the sun, the conversion of mass into energy releases such a large amount of energy per atom that only an infinitesimal fraction of the sun's mass (about one-millionth of one-millionth) is used up each year. The sun should continue to radiate at almost the same rate for many billions of years to come.

Reactions involving light elements such as lithium and deuterium appear to play a role in the energy emission from stars of the red giant type. The extreme densities of white dwarf stars, perhaps hundreds of times the density of water, are supposed to be connected with the existence of cores of closely packed neutrons. Thus, at last, science seems to be answering the question as to the source of stellar energy.

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SUMMARY

Natural alpha particles have enough energy to penetrate into a light nucleus if a rare "direct hit" is made. In 1919, Rutherford found ***protons*** (hydrogen nuclei) thrown out from nitrogen nuclei when bombarded by alpha particles—the first nuclear reaction.

Apparatus for accelerating nuclear projectiles includes the high-voltage transformer with rectifiers and ***discharge tube,*** the Van de Graaf generator with discharge tube, and the ***cyclotron.*** The cyclotron builds up the effect of a high voltage by using a comparatively small voltage many times.

In 1932, Chadwick identified the ***neutron,*** an uncharged particle slightly heavier than the proton. The neutron is very penetrating and enters nuclei readily.

All nuclei consist of neutrons and protons. In a nucleus, the number of protons equals the number of elementary charges (the atomic number), and the total number of neutrons and protons equals the mass number. The sum of the masses of the total number of neutrons and protons is always greater than the nuclear mass if the nucleus is stable. This difference (in energy units) is just the ***binding energy*** of the nucleus.

Repulsive electrical forces between protons in the nucleus must be offset by some attractive force. This ***nuclear force,*** which holds nuclei together, acts only at small distances (less than 2×10^{-13} cm).

In an energetic nuclear collision, there may be formed a highly unstable ***compound nucleus*** which almost immediately throws out a nuclear fragment, usually proton, neutron, or alpha particle, frequently with a gamma-ray quantum.

In a nuclear reaction the sum of the initial mass and energy (in the same units) must equal the corresponding final sum. Thus, the laws of conservation of mass and energy must be combined: ***The sum of mass and energy (in the same units) remains constant.***

Frequently nuclear reactions result in radioactive nuclei which subsequently emit positive or negative electrons and usually gamma rays. These positive or negative electrons are supposed to be "created" during a nuclear rearrangement. This is made plausible by observations of the "creation" of positive and negative electron "pairs" from gamma rays.

The slower a neutron, the more effective it usually is in producing radioactive elements. Fast neutrons may be slowed down most effectively by materials rich in hydrogen.

Radioactive and stable isotopes of the same element have virtually identical chemical properties. Thus a small fraction of a radioactive isotope in an element as a "tracer" can indicate, by electrical detectors, the course of the element in physical, chemical, or biological processes. Artificial radioactivity may with advantage supplement radium and X rays in therapy.

In 1939, it was discovered that a slow neutron can split one kind of uranium nucleus into two nearly equal fragments, releasing much more energy per nucleus than reactions in which a small nuclear fragment is emitted. In this reaction, called ***fission,*** slow neutrons are released after the initial breakup. There is a possibility, as yet unrealized, that these neutrons can propagate the reaction and thus provide a continuous release of useful nuclear energy.

QUESTIONS

1. Why was it difficult to find a projectile that would penetrate the nucleus?
2. What particles were first used successfully to produce nuclear transmutations? By whom?
3. What methods are now used to give particles enough energy to disrupt nuclei?
4. Of what advantage is the ***cyclotron*** system of accelerating particles to high energy in small steps?
5. What is the ***neutron?*** When was it discovered?
6. For what reasons are nuclei believed to consist only of neutrons and protons?
7. What is meant by the ***binding energy*** of a nucleus?
8. What holds nuclei together? Why would ordinary electrical forces not serve for this purpose?
9. How does the modern alchemist produce his results?
10. In what way have studies of nuclear reactions confirmed the idea that there is an equivalence between mass and energy?
11. In mass-energy conversions 1 mass unit is equivalent to 931 MEV. Can you verify this statement? (The mass of O^{16} is 2.64×10^{-23} g, and the charge on the electron is 1.60×10^{-19} coulomb.)
12. How can our old statement of the principle of conservation of energy be modified to be strictly accurate?
13. How are artificial radioactive elements produced?
14. What differences usually exist between the types of radiation from artificial and from natural radioactive nuclei?
15. When was the positron discovered? Under what circumstances?
16. What experiment lends plausibility to the idea that electrons can be "created"?
17. What energy in million electron-volts is equivalent to the mass of an electron pair? (The mass of a positive or negative electron is 9.0×10^{-28} gram.) What minimum gamma-ray quantum energy is needed to create an electron pair? What happens to the

excess energy when a pair is created by a gamma-ray quantum with energy greater than this minimum value?

18. Is there any inconsistency in the statement that slow neutrons may be very effective in producing nuclear transmutations while protons, deuterons, and alpha particles require very high speeds in order to enter nuclei?
19. How are radioactive "tracers" used?
20. In what way do neutrons affect living cells?
21. What type of material can best "shield" living tissue from neutron radiation?
22. Are ordinary nuclear reactions likely to become practical sources of energy?
23. How does the "fission" process differ from other nuclear reactions?
24. Why has the discovery of fission revived the hope of practical atomic power? What difficulties stand in the way of realization of this hope?
25. What connections are there between nuclear physics and astronomy?

CHAPTER XXII

COSMIC RAYS

It has long been known that charged electroscopes gradually lose their charge in spite of all efforts to prevent the loss. Of course some of this "leakage" is the result of imperfect insulation, and some is from ionization produced by small residual amounts of radioactive materials in the walls of the electroscope. However, by 1901, it was demonstrated that, when such factors were minimized and their effects taken into account, a definite leakage ***still*** existed. This could be explained only if ordinary air were being ***continuously ionized*** to a slight extent by some radiation coming from outside the electroscope. To surround the electroscope with lead a couple of inches thick helped some, and many thought that radiation from residual radioactive materials in the ground and buildings could account for the remaining leakage.

Discovery of Cosmic Rays. In 1911, Gockel and then Hess finally took electroscopes on balloon flights and discovered that at first the ionization really did decrease as the electroscope was taken above the earth, because of the increased distance from the residual radioactivity in the earth's crust. Hess demonstrated, however, that at 1,800 meters height the ionization actually began to ***increase,*** and that at 5,000 meters it was 16 ***times as great*** as on earth. Hess rightly concluded that this effect must be caused by a very penetrating radiation, which is most likely of extraterrestrial or cosmic origin. That the radiation could be observed at sea level after passing through the whole atmosphere, equivalent in mass to a layer of mercury 76 cm in thickness or 10.5 meters of water, showed that it must be extraordinarily penetrating. Since from day to night there was virtually no change in the intensity, it was seen that no appreciable portion of this ***cosmic radiation*** comes from the sun.

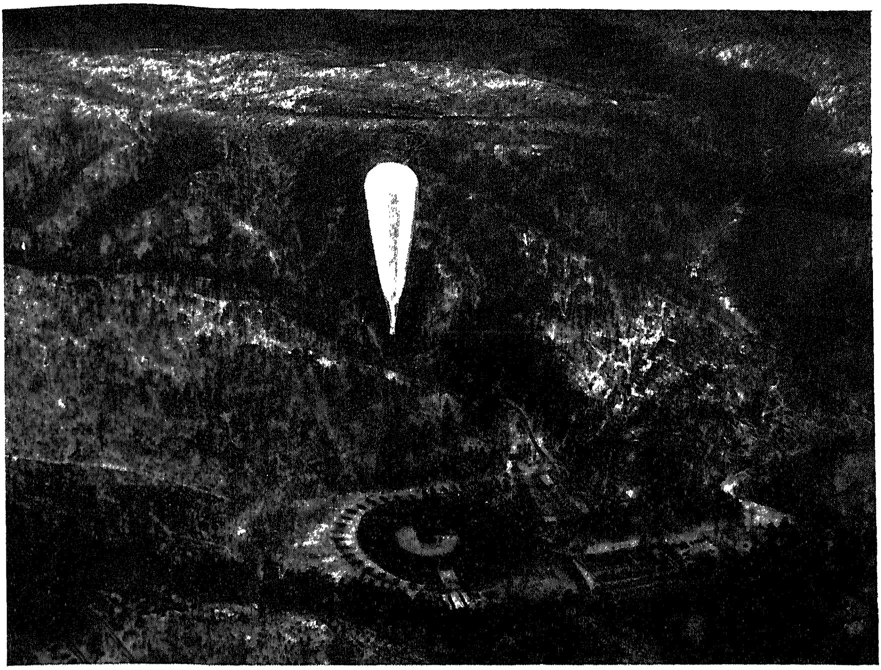

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Fig. 500. Explorer II beginning highest ascent made by man. The balloon contained 250,000 cu ft of helium at the take-off. When it had risen twelve miles above sea level its gas had expanded, completely filling the 3,700,000 cubic foot bag.

The Explorer II carried into the stratosphere more than a ton of scientific instruments including automatic recording apparatus for studying cosmic radiation.

Penetration of Cosmic Rays. In 1918, after the end of the war, cosmic ray research efforts were intensified. Among the most active workers in this field were Hess, Kohlhörster, Regener, and Blackett in Europe, and Millikan, Compton, Johnson, and their collaborators in America. To measure the variation in cosmic radiation intensity as the upper part of the atmosphere is approached, photographic recording electroscopes and sensitive Geiger-Mueller counters were sent up to ever greater altitudes by balloons. Expeditions went all over the world, to the equator and the polar regions, to high mountains and to deep mines. Some workers lowered electroscopes to great depths in lakes to determine how much matter cosmic rays can penetrate.

Figure 501 shows how the cosmic ray ionization was found to vary with amount of matter penetrated. The intensity increases markedly with increasing height above sea level, but near the very

"top" of the atmosphere the ionization begins to decrease somewhat. Of course, there is no real limit to our atmosphere, but unmanned automatic balloons have now been sent up to heights where the pressure is less than 0.35 cm Hg, as compared with 76

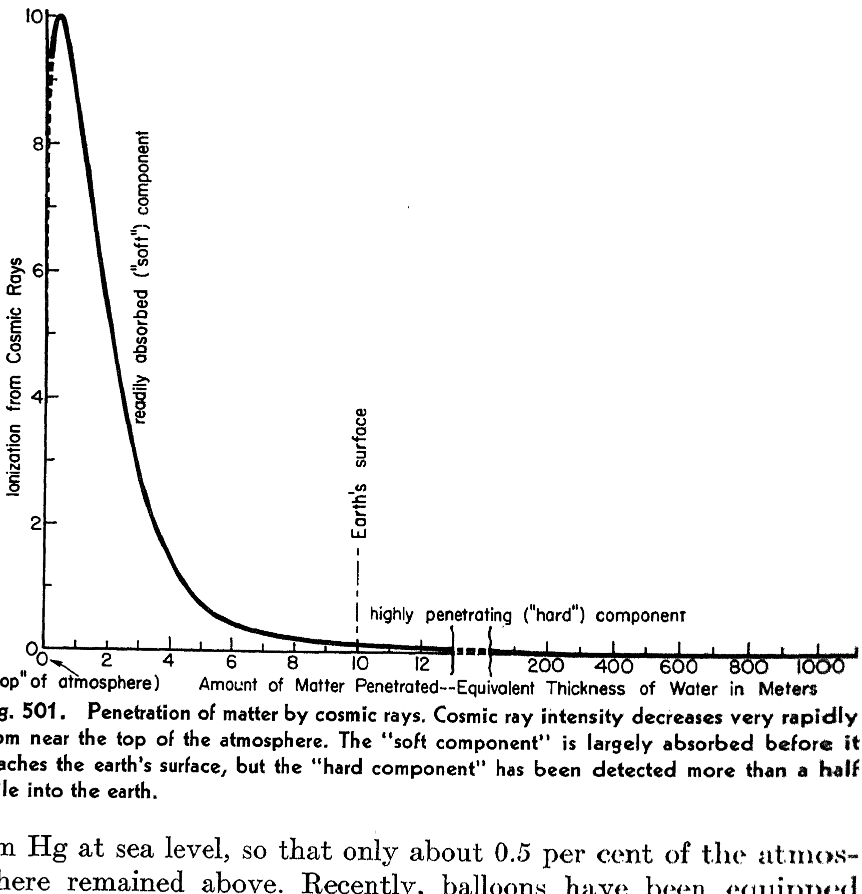


Fig. 501. Penetration of matter by cosmic rays. Cosmic ray intensity decreases very rapidly from near the top of the atmosphere. The "soft component" is largely absorbed before it reaches the earth's surface, but the "hard component" has been detected more than a half mile into the earth.

cm Hg at sea level, so that only about 0.5 per cent of the atmosphere remained above. Recently, balloons have been equipped with tiny radio transmitters which automatically send back to a receiver on earth records not only of cosmic ray intensity, but also of barometric pressure, humidity, and temperature. Such balloons have the advantage that they need not be recovered after they come down in order to secure the record of the flight.

At the other extreme, some cosmic rays were found to penetrate the equivalent of 1,000 meters of water! An examination of Fig. 501 shows that there are probably at least two major components in the cosmic radiation, one component (referred to as "soft") which

is mostly absorbed before reaching the earth, and a very penetrating ("hard") component which goes through enormous thicknesses of matter.

The Earth's Magnetic Field and Cosmic Rays. If, as many suspected early, a good part of the cosmic rays are high-energy charged particles such as electrons (positive and negative) or protons, then, it was reasoned, the earth's magnetic field, which though weak extends far out into space, ought to act on them as a gigantic spectrograph. The intensity of cosmic ray particles should be higher near the magnetic poles than near the equator, for the following reason. We recall (page 451) that charged particles crossing a magnetic field are deflected so that they follow curved paths, and the greater the energy of the particles the less their paths are affected by the field. Now, cosmic ray particles originally directed toward the earth's equator must *cross* the earth's magnetic field, so at least the less energetic ones should be deflected enough to miss the earth completely. On the other hand, most of the particles directed toward the magnetic poles would travel *along* the direction of the magnetic field instead of across it, so their intensity at the earth would be almost unaffected by the field. In other words, the cosmic ray intensity at the earth's surface should vary with latitude.

The expeditions to all parts of the earth disclosed that this "latitude effect" did exist, for the intensity near the poles exceeded that near the equator by amounts varying from 14 per cent on the earth's surface to 33 per cent at higher altitudes. Thus it was proved that cosmic rays must consist at least in part of *charged particles.* However, this did not exclude the possibility that there are also some high-energy quanta or some neutral particles in cosmic radiation. In fact, we have learned that quanta can create electron pairs or pull electrons out of materials, so it is difficult to be sure what the *primary* rays coming to us from interstellar space really are—the energetic charged particles observed might be produced in the upper atmosphere by photons through pair production, the photoelectric effect, or scattering.

Cosmic Ray "Telescopes." Ingenious experimenters have arranged two or more particle counters to make cosmic ray "telescopes." If two counters were used, particles coming from the proper direction to pass through *both* counters in succession would be recorded by a so-called "coincidence circuit." By pointing such

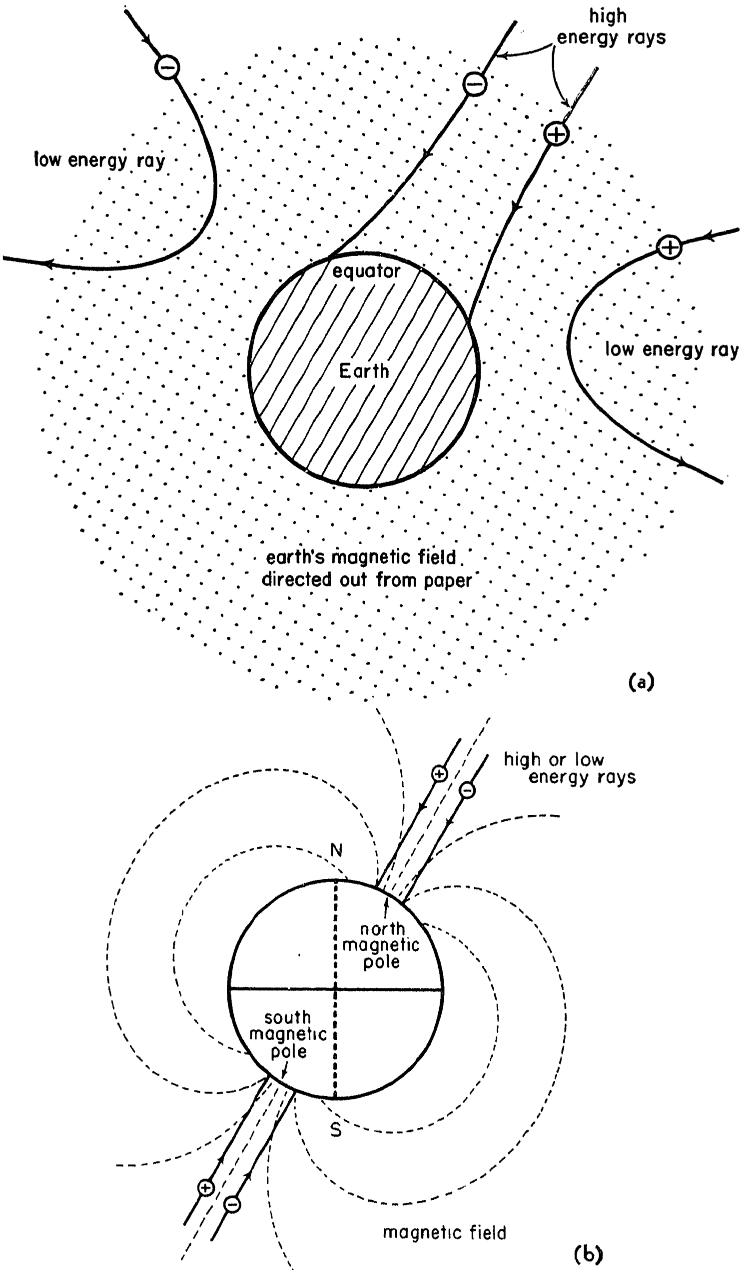


Fig. 502. Cosmic-ray intensity varies with latitude. The cosmic-ray intensity is greater near the magnetic poles than near the equator. (a) Some cosmic-ray particles initially directed toward the earth's equator are deflected away by the earth's magnetic field which they cross. (b) Cosmic-ray particles directed toward the earth's magnetic poles follow the "lines of magnetic force" (instead of crossing them) so are relatively unaffected by the earth's magnetic field.

a "telescope" toward the heavens, the intensity of cosmic rays coming from that particular direction could be measured. It was found that more cosmic ray intensity comes from directly overhead than from any other direction, and that almost no cosmic rays

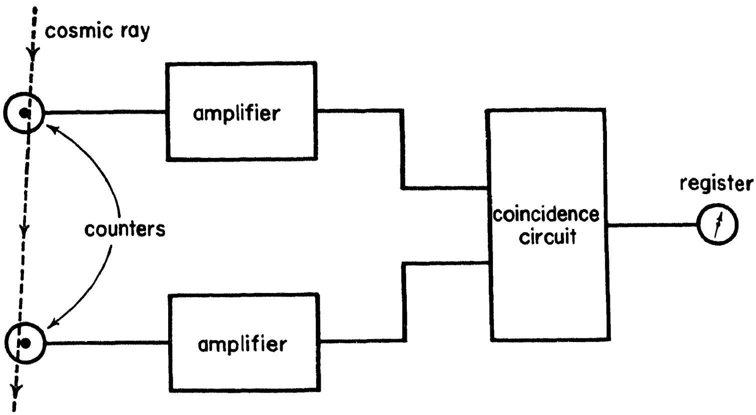
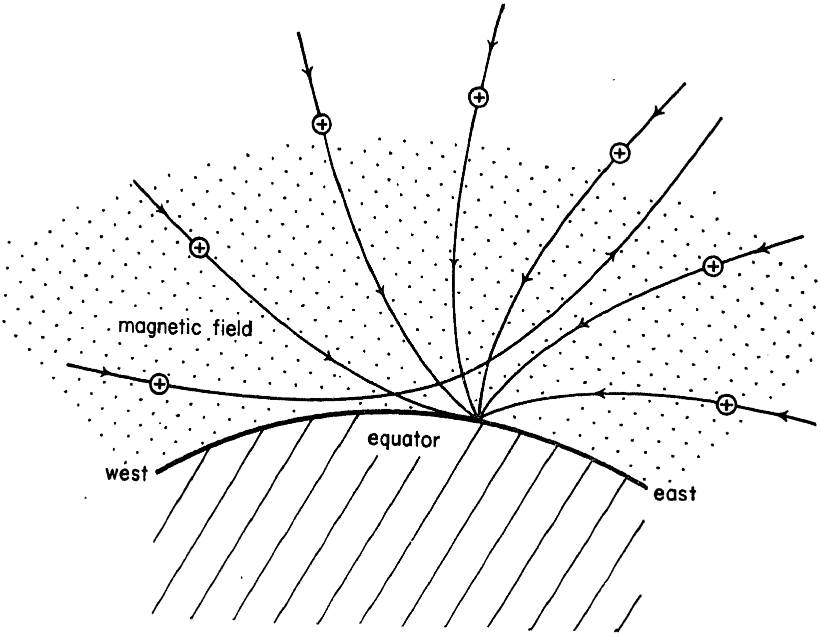


Fig. 503. Simple cosmic-ray "telescope." To be recorded, a cosmic ray must pass through both counters. Consequently the approximate direction of all recorded cosmic rays is known from the relative orientation of the two counters.

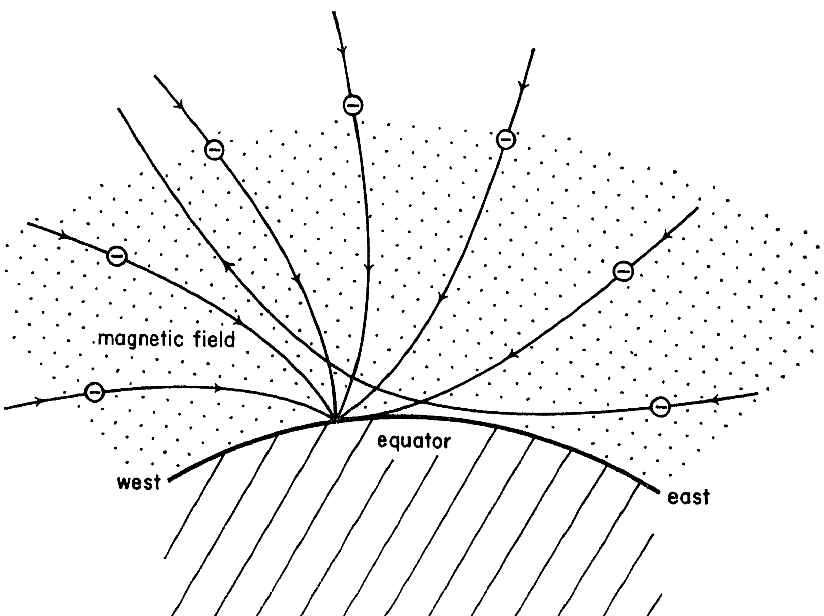
come from the sides. There was, however, an appreciably greater intensity of rays coming from directions inclined to the west of the meridian than from those to the east. This could be explained only if the rays deflected by the earth's magnetic field were predominantly positive in charge.

New Light on Cosmic Rays. In the hands of many observers, including Carl D. Anderson and P. M. S. Blackett, the Wilson cloud chamber proved to be a revealing tool for the study of cosmic rays. When placed in a magnetic field, not only did it show the cloud tracks of cosmic ray particles, but it also showed that these paths were curved by the magnetic field, and from the curvatures the energies (or momenta) of the particles could be determined. As might have been expected from the penetrating power of the radiation, studies of the bending of the tracks showed that cosmic rays had energies of a new order of magnitude—larger than anything known before. Many particles with energies of 100 million electron-volts were observed in cloud chambers, and measurements extended to 1,000 and sometimes even 10,000 million electron-volts.

Positrons and Electrons. As we learned (page 623), Anderson, in cloud-chamber experiments, discovered the ***positron,*** or positive



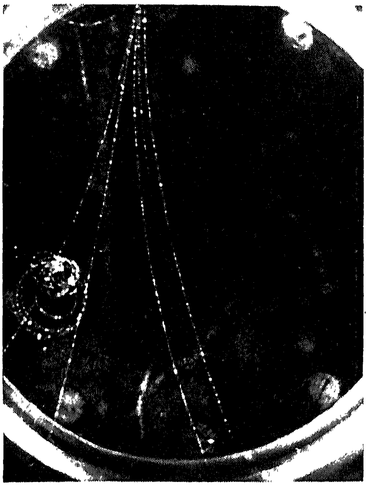
(a)



(b)

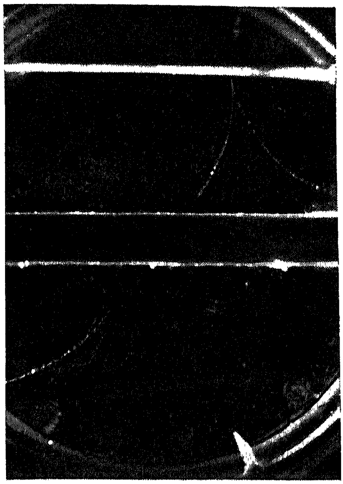
Fig. 504.—For descriptive legend see opposite page.

electron, which has the same mass as the ordinary electron but an opposite charge. For a long time it was thought that all tracks that looked like negative electron tracks but were curved oppositely must be caused by electrons going the other way. However, these



(C. D. Anderson.)

Fig. 505. Cloud tracks of positive (deflected to right) and negative cosmic-ray particles in a strong magnetic field. Note the "tight" circles into which paths of low-energy "secondaries" are curled.



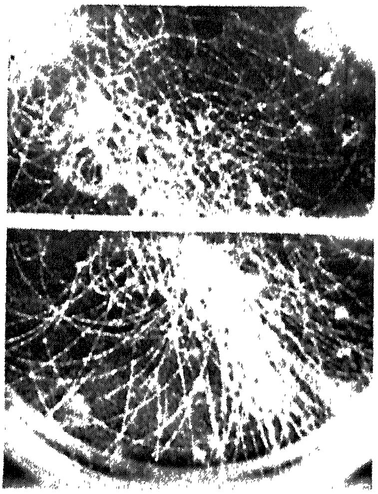
(C. D. Anderson.)

Fig. 506. Cloud tracks of a positive and negative electron "pair" produced in a lead sheet by a cosmic-ray photon. An intense magnetic field gives opposite curvatures to the two tracks. One of the particles passes through a lead plate several centimeters thick, emerging below with reduced energy.

oppositely curved tracks are very abundant in cosmic rays, and Anderson showed conclusively that they are practically all due to positive electrons. It was also discovered that, when a gamma-ray quantum having an energy greater than 1.1 MEV (which is the energy equivalent of the mass of two electrons) passes near an

Fig. 504. "East-west effect" on cosmic ray intensity. From the fact that cosmic ray intensity from west of the zenith is greater than from the east, it has been concluded that the cosmic-ray particles that enter the earth's field are predominantly positive. (a) Positive cosmic ray particles initially coming uniformly from all directions are deflected by the earth's magnetic field so that at the earth's surface they come in greatest intensity from west of the zenith.
(b) Similarly negative particles come from the east. Thus, a predominance of particles from the west indicates that more positive than negative cosmic-ray particles must enter the earth's magnetic field.

atomic nucleus, it may be converted into a "pair" consisting of a positive and negative electron. This is an instance of energy being converted into matter. That there are many energetic gamma rays accompanying cosmic rays followed directly from the identification of many such "pairs" in cloud-chamber photographs of effects of cosmic radiation.



(C. D. Anderson.)

Fig. 507. Cloud-chamber record of a cosmic-ray shower. An intense magnetic field shows the presence of an enormous number of both positive and negative particles. The shower appears to be more intense below the central absorbing plate.

Subsequent work with atom smashing techniques has shown that positrons lead a very transient existence, for they usually combine quickly with a negative electron. They die in a blaze of glory, and the energy represented by the mass of the uniting particles is radiated as a gamma-ray quantum of about 1.1 MEV, or as two quanta, each with half this energy. Thus matter may be converted into pure energy.

Cosmic Ray Showers. Workers with electroscopes observed long ago that occasionally an electroscope leaf suddenly jumps as though a great "burst" of ionization occurs. Later the cloud chamber revealed that sometimes a great many positive and negative electrons are produced in a small space, as though all the energy of a cosmic ray suddenly brought about an atomic explosion. Some comparatively heavy nuclear particles were also observed in these "showers." According to recent researches, a single cosmic ray "shower" may spray electrons over a region as great as 100 meters in diameter. It has been calculated that the energy released in one of these bursts may be as much as 10^{18} electron-volts. Cosmic ray bursts increase rapidly in frequency if the cloud chamber is taken to a high altitude, say to a mountain top.

Neutrons in Cosmic Rays. Recent work has disclosed that neutrons are present in cosmic rays in large numbers. It is doubtful whether the neutrons are part of the radiation which originally enters the atmosphere (the ***primary*** rays). We should expect that they can be accounted for completely as ***secondary*** particles

released when energetic cosmic rays disrupt nuclei in the atmosphere.

The Mesotron. To complicate the situation still further, there is increasing evidence of still another very important type of

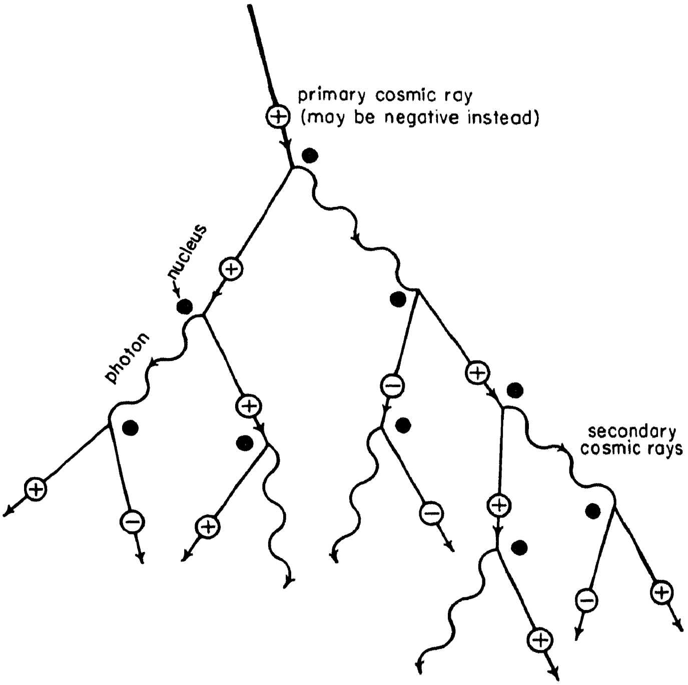
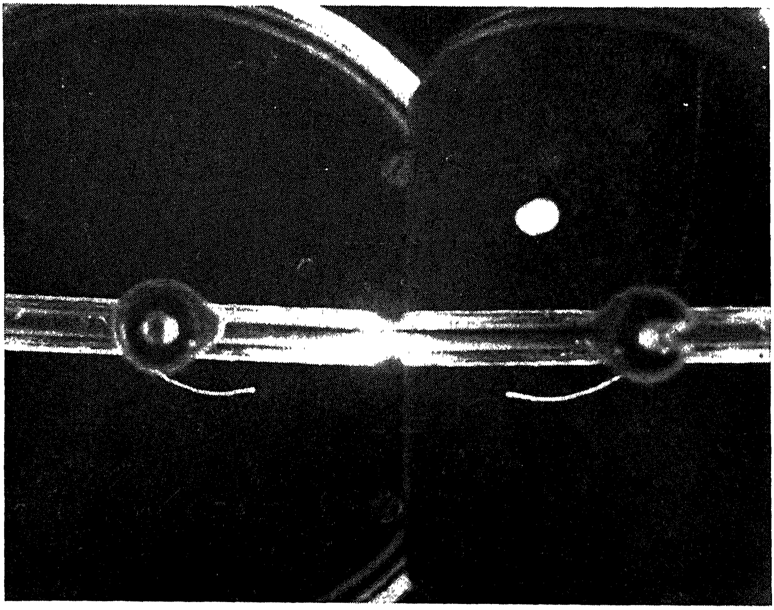


Fig. 508. Schematic description of the production of a great many secondary cosmic rays by a single primary cosmic ray entering the earth's atmosphere. High-energy charged particles radiate quanta when passing through matter, and the quanta in turn produce positive and negative electron pairs near nuclei (black dots); thus the multiplicative process carries on. (The angles of the "forks" are greatly exaggerated.)

particle present among cosmic rays—one which was hitherto unknown. The great penetration of the hard component of the cosmic radiation seems much too large to be caused by the light electrons or positrons, the absorption laws of which are fairly well known. On the other hand the penetration is not that to be expected from the more massive protons, 1,840 times heavier than electrons. A particle of intermediate mass should have more nearly the penetration actually found.

In the last few years, long investigations in cloud chambers, involving thousands of pictures, have resulted in a number of photographs of tracks that have just about the right curvature

and density to correspond to a particle nearly 200 times heavier than the electron. This and many other bits of evidence make it seem highly probable that the penetrating portion of the cosmic radiation is indeed made up of what have been named ***mesotrons.***



(*C. D. Anderson.*)

Fig. 509. Cloud track of heavy particle, probably a mesotron that passes through a counter within the cloud chamber, then comes to rest in the gas of the chamber (direct and reflected view). A magnetic field through the chamber shows that this mesotron was charged positively.

These particles seem to have the same charge as the electron and can be positive or negative, or perhaps neutral, but possess about 200 times the electron's mass. There is evidence that the mesotron is unstable and tends to disintegrate in about one-millionth of a second. Possibly it breaks up into an electron and a neutrino, that hypothetical neutral particle which we have met in connection with beta radiation (page 623). The "soft" component of the cosmic radiation, which is largely absorbed before it reaches the earth's surface, very likely consists mainly of electrons and positrons.

The Realm of High Particle Energy. The study of cosmic rays has suggested that there are many new secrets of matter and energy which research may reveal. Whence come the enormous

energies of billions of electron-volts in cosmic rays? Are they flung out from stars evolving in far-away parts of the universe, or from exploding stars in distant space? Or are they perhaps due to the acceleration of charged particles by enormous potential differences

(*Wide World.*)

Fig. 510. A. H. Compton with cosmic-ray "telescope." Mounted at the left are a number of counter tubes connected in coincidence to respond to cosmic rays from a definite direction.

between various parts of stars or between other accumulations of matter in cosmic space? There is actually some evidence of a slight preponderance of rays coming from one direction in the universe.

Have cosmic rays always been raining on the earth at the same rate as now? We know that several times each second such rays pass through each of us, destroying some of our cell structure. Perhaps the cosmic rays cause disturbances in hereditary factors, and thus contribute to the production of mutations, or changes, in plants and animals. Exposure of animals to neutrons and X rays in the laboratory does produce appreciably increased mutation rates. Thus it may be that cosmic rays have played an important role in evolutionary development. Such intriguing questions make

interesting speculation, and future researches may bring us answers to these and unsuspected new questions which today we cannot even formulate.

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SUMMARY

In 1911, Hess discovered an ionizing radiation of great penetrating power, which increased in intensity with height in the atmosphere. This ***cosmic radiation*** is of extraterrestrial origin and does not come from the sun in appreciable intensity. It consists of a "soft" component, mostly absorbed by the atmosphere, and a "hard" component, some of which can penetrate more than 1,000 meters of water.

Cosmic rays are less intense near the equator than near the earth's poles. This would result if the "primary" radiation consists partly of charged particles which are deflected by the earth's magnetic field. That the deflected charges are predominately positive seems to be indicated by the fact that the intensity from the west of the meridian is greater than that from the east.

From curvatures of cloud-chamber tracks in a magnetic field, energies of cosmic ray particles have been found to extend at least to 10^{10} electron-volts. In cosmic radiation, Anderson discovered both the positron and electron "pairs" created from gamma-ray quanta. Occasionally cosmic rays produce in matter great showers of positive and negative electrons and nuclear particles. Neutrons in cosmic radiation are probably from disrupted nuclei, that is, nuclei of "secondary" origin. Cloud-chamber tracks of a new particle, the ***mesotron,*** are also found. This particle has the same charge as the electron (positive or negative) and about 200 times its mass. It seems to be unstable, with a half-life of about 10^{-6} sec.

Cosmic radiation may have some influence on evolutionary changes by disturbing *genes* or hereditary factors in organisms.

QUESTIONS

1. How did Hess demonstrate the existence of *cosmic radiation?*
2. How do we know that cosmic rays have a very great penetrating power?
3. What is meant by "hard" and "soft" components of cosmic radiation?
4. Why do we believe that cosmic radiation entering the earth's atmosphere consists at least partially of charged particles? What is the evidence that more of these particles are charged positively than negatively?
5. How are the energies of cosmic ray particles measured? To about what value are they known to extend?
6. What is the meaning of the statement that neutrons in cosmic radiation are probably of "secondary" origin?
7. What are cosmic ray *showers?*
8. What particles were first discovered in cosmic radiation? What are their characteristics?
9. What do we know about the origin of cosmic rays?
10. In what way is it possible that cosmic radiation influences evolutionary changes?
11. How do we know that part of the cosmic radiation reaching us consists of energetic gamma radiation?
12. How completely bridged are the gaps which formerly existed between the various classifications of electromagnetic waves?

CHAPTER XXIII

MATTER, ENERGY, AND RADIATION

THE ELECTROMAGNETIC SPECTRUM

Our studies of radiation have shown that the long radio waves, infrared, visible, and ultraviolet light, X rays, gamma rays, and the high-energy photons in cosmic rays are all essentially the same type of electromagnetic radiation. The distinctions we make between the various waves are not at all sharp and are purely for convenience. The experimental evidence indicates that all these waves originate from transitions involving electric charges. All travel with the same speed in vacuum, 3×10^8 meters/sec or 186,000 miles/second. They differ only in frequency or wave length, and all follow the same fundamental relation of wave motion

$$\text{Velocity} = \text{frequency} \times \text{wave length}$$

The differences which these electromagnetic waves display when they pass through matter arise only because of their different frequencies or wave lengths. Gamma rays which have wave lengths much smaller than an atomic "diameter" naturally pass through the vast open spaces inside an atom with comparative ease, while very long infrared waves or radio waves with lengths much larger than atomic dimensions behave quite differently. As we have also seen, all electromagnetic waves are emitted in units or quanta with energy proportional to the frequency

$$\text{Energy} = h \times \text{frequency}$$

and most phenomena depend upon the energy per quantum, hence upon the frequency.

It is interesting to see that the range of magnitudes of frequency and wave length so far investigated runs from nearly zero to nearly infinite values. Even a 60-cycle power line radiates an electromagnetic wave, but the wave length (from velocity = frequency ×

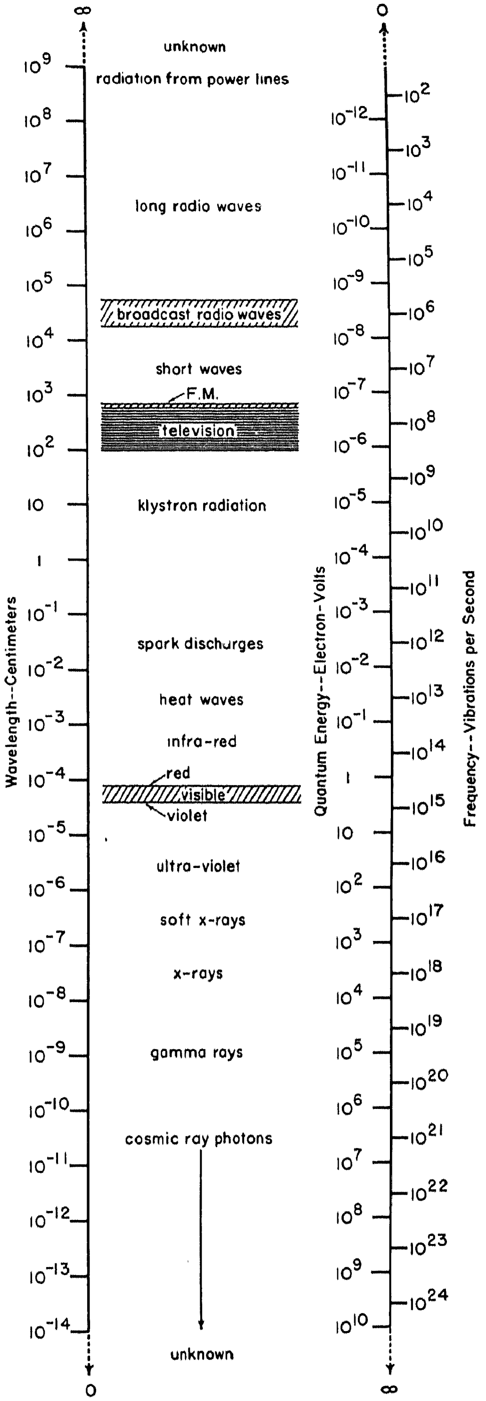

Fig. 511 Known electromagnetic spectrum

wave length) is about 5×10^8 cm or about 3,000 miles! At the other extreme lie the cosmic ray photons, some of which have frequencies as high as 3×10^{24} per second or wave lengths of 10^{-14} cm. Throughout this range, quantum energies vary from about 0.2×10^{-12} electron-volt for the 60-cycle radiation to greater than 10,000 million electron-volts for cosmic ray photons.

The distinctions between the various regions represented in Fig. 511 are largely due to the fact that these different parts "grew up" separately, and different techniques were applied to their study. Consequently, different terminologies developed in many cases before it was realized that all parts belong to the same "electromagnetic spectrum." All the arbitrarily named regions throughout the entire spectrum overlap, extending over a range of 10^{28} times. In the beginning, man's only knowledge was about radiation in the comparatively narrow visible region which his eyes could detect. Research has continually extended his knowledge to include both higher and lower frequencies. What lies beyond the known frequency values is an interesting question, particularly in the uncertain region of still shorter waves and higher frequencies.

DISTANCES IN THE UNIVERSE

The range of distances which scientific investigations have now covered is likewise enormous. From the smallest dimensions studied, about 10^{-13} cm, the effective diameters of such fundamental particles as neutrons and protons, on up through microscopic and visible regions, and then out to our solar system and the most distant nebulae reached by the largest telescopes, there is a range of about 10^{40} times in distance! In the course of man's search for knowledge concerning the universe, he has extended, toward great and small, the range of distances with which he is acquainted. He began with those, near the center of Fig. 512, which he could see directly and measure with very crude measuring sticks. Surely, the limits have not yet been reached.

MATTER, ENERGY, AND RADIATION

Our investigations of matter, energy, and radiation have led us a long way toward accurate descriptions of phenomena in nature. We have seen how continued patient research by curious men over many ages has opened whole new vistas of thought and

how this thought has accelerated scientific progress. All matter, as we have learned, is built of a few fundamental particles such as neutrons, protons, and electrons, which, when examined closely, exhibit properties of waves as well as particles. Electromagnetic radiation, when subdivided finely, appears to be transferred in ultimate energy units which we call quanta and which behave like concentrated lumps of wave energy. The conversion of matter into energy, and vice versa, we have found on earth. Moreover, we are now quite certain that the conversion of matter into energy is the source of the energy that streams to us from the sun.

Progress in physics has brought us now to a point where we see that the three major types of entity in nature, matter, energy, and radiation, are actually very nearly the same thing. By the proper methods each may be converted into the other.

SCIENCE AND SOCIETY

New knowledge of the world around us is accumulating faster and faster, and will give us ever-increasing ability to control our environment. The success already achieved in utilizing our knowledge of matter, energy, and

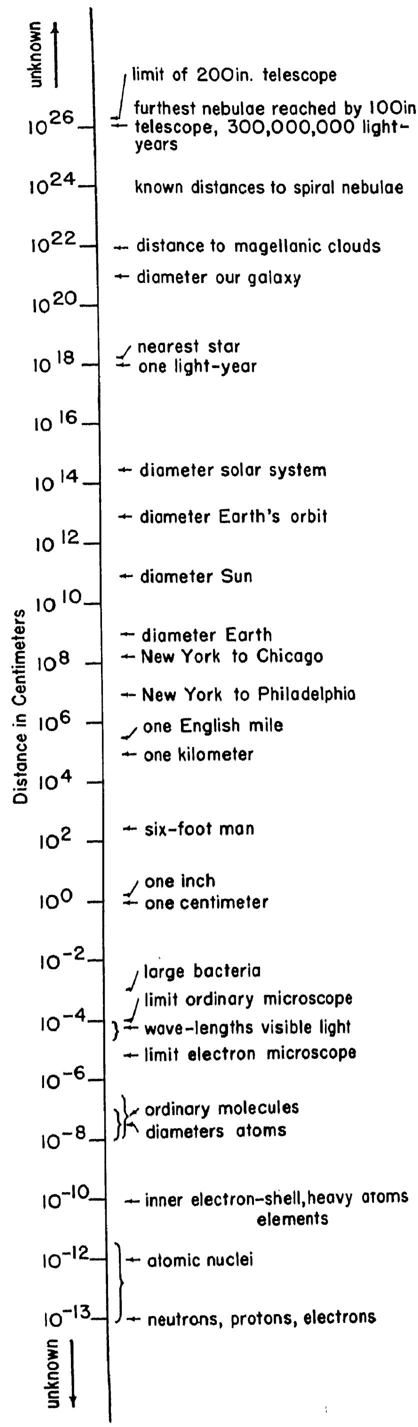

Fig. 512. The unfolding universe.

radiation, has greatly influenced nearly every aspect of life. New applications of scientific principles are affecting all areas of human activity, social, political, and economic. Most important of all, however, is the steady, although painfully slow, growth of the scientific attitude and the use of objective experimental methods.

Our rapidly increasing use of energy has now brought us to a point where, of the total energy utilized in this country, manpower accounts for only a little more than 1 per cent! The transition from the period when practically all work was done by man has left us many serious problems, but there is abundant evidence that we can find satisfactory solutions for them. Energy controlled constructively for the benefit of man is the keynote for the future.

In the beginning of the industrial era many feared that men were becoming slaves to machines and that continually increasing armies of men would toil and sweat in huge smoke-blackened factories amid the grime and the roar of machinery.

Today, as the new era of power comes of age, machines and production processes are becoming more and more automatic throughout all industries. Consequently, more and more workers are now becoming technical supervisory experts who watch dials and make inspections or adjustments in modern fluorescent-lighted plants. Increasing numbers of men must use intelligence and trained judgment to direct electrical energy through automatic mechanisms which turn out goods never touched by hand. Men must guide such machines, and to do so, they must understand the processes. Men are undoubtedly the masters of machines.

In this new age, the "submerged masses," the so-called proletariat, should continue to disappear and the whole of human activity be freed and lifted to levels in keeping with the dignity of man.

APPENDIX

THE LABORATORY IN THE SCIENCE PROGRAM

The experimental basis of science is so important that we believe it highly desirable for a student to have an opportunity to experiment for himself. Such first-hand experience in the methods and techniques of the scientific fields has much to contribute to an understanding of science and its accomplishments and to an appreciation of the way in which science develops. In some institutions, it might not be possible to provide laboratory experience in a course in science, but abundant lecture demonstrations serve as a partial substitute.

At Columbia University, laboratory work has proved so valuable an aid to the science program that some suggestions for the laboratory are included here.

For a coordinated science program, considerable freedom to depart from the more conventional laboratory work seems desirable. Many students toward whom a science program is directed find the traditional laboratory procedure often far from inspiring, but, properly dealt with, it seems possible to revitalize the laboratory work so that it is the most interesting part of the course and at the same time remains a most effective teaching aid.

Group experiments in small sections under the guidance of an instructor offer interesting possibilities. Intelligently led, this procedure gives a great deal of stimulus through the inspiration of common effort. Individual experiment, however, has a real place and should not be neglected. As a compromise, working in pairs is often quite satisfactory. We have chosen experiments on the basis of both fundamental importance and intrinsic interest. There has been an attempt to develop each experiment so that its fundamental points are as clear cut as possible. Large-scale apparatus rather than toy models seems to be more effective in capturing interest and in driving home essential ideas. Furthermore, emphasis on the phenomena under study and on the main ideas seems more 'mportant for such a course than precise quantitative measurements.

The outline below refers to the Science A1 Laboratory schedule at Columbia University.

The Tools of the Astronomer:

Lenses, mirrors, and telescopes. Formation of images by convex lenses and concave mirrors. Construction of simple refractor telescopes by two simple lenses. Measurement of focal distances and magnification. Construction of simple reflector telescopes by concave mirrors, with small auxiliary mirror and eyepiece lens.

Methods in Astronomy:

Visit to observatory. Study of construction of astronomical refractors and reflectors. Equatorial mounting and star position measurements. Declination and right ascension. Determination of sidereal time. Transits and sextants.

Introduction to Physical Measurements—Properties of Matter:

Density of typical solids and liquids by use of simple balances, calipers, and graduated cylinders. Density of air by change in weight of evacuated metal spheres.

Mechanical Energy and Efficiency of Machines:

Measurements of work. Energy input and output of a number of large pulley systems. Conversion of potential energy to kinetic energy. Potential energy of loaded low-friction carrier (roller skate) at top of inclined plane, and its kinetic energy from speed measurements on level after rolling down incline. (Incline and table initially set at friction angle.)

Heat and Mechanical Energy:

Measurement of heat energy. Conversion of mechanical to heat energy, studied by temperature rise of lead shot falling repeatedly through tube. Mechanical equivalent of heat by Callendar, or similar, apparatus.

Heat and Changes of State:

Heat of vaporization of steam condensed in water in calorimeter, from temperature rise and initial and final weights. Heat of fusion of ice melted in water in calorimeter, from temperature drop and initial and final weights.

Electric Energy:

Measurements of voltage, current, and resistance in simple series and parallel circuits with voltmeter and ammeter.

Conversion of Electric Energy to Heat Energy:

Measurement of heat energy added to water in calorimeter by electric energy dissipated in immersed resistance coil.

Electric and Mechanical Energy:

Measurement of efficiency of electric motor at various loads by electric energy input and mechanical energy output to a Prony brake.

Kinetic Theory of Gases:

Gas laws. Measurement of pressures in constant volume thermometer corresponding to temperatures ranging from the boiling point of water to that of dry ice and liquid nitrogen.

Electron Tubes:

Diodes. Electron emission from hot filament at various temperatures. Saturation current. *Triodes.* Effect of grid potential on electron current. Amplification.

Light and Spectroscopy:

Interference and diffraction of light. The grating. Prism or grating spectrometer and measurement or inspection of continuous and line spectra.

Radioactivity:

Detection of alpha particles with cloud chamber. Measurements of alpha particles with Geiger counter. Range. Statistical fluctuations of number of individual particles. Cosmic ray detection.

Research Laboratories:

Visit to research or advanced laboratories to gain some appreciation of research methods. Laboratories devoted to X ray, electronics, spectroscopy, solid state studies, to nuclear physics, the cyclotron, or high-voltage apparatus are satisfactory.

Supplementary field trips to places which illustrate applications of science outside of the university, such as power plants, communication systems, transportation systems, as well as museums of science and industry, the planetarium, etc., have been very stimulating.

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